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DETERMINATION OF THRESHOLD DAMAGE IN RADOME MATERIALS BY DISCRETE IMPACT IN A BALLISTICS RANGE

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The techniques and results for the determination of threshold impact damage of control materials and of a slip cast fuzed silica are presented.

The preliminary results on drop distortion and drop stripping are observed and compared with analytical estimates.

Data were obtained for several materials with water droplets of approximately 1mm diameter. Data were also obtained for limited conditions with .050" and .070" diameter lead spheres. Velocities from approximately 300 feet per second through 3500 feet per second were obtained, depending upon the material under investigation.

The major effort in this program phase was the investigation of slip cast fuzed silica at a pressure of one atmosphere. Distinct and repeatable damage thresholds were observed with water impact on this material.

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The use of the Laboratory Aerophysics Range has proven to be a rapid and economical means of obtaining valuable information on discrete impact and materials response.

NAVAL ORDNANCE LABORATORY
Silver Spring, Maryland

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DETERMINATION OF THRESHOLD DAMAGE IN RADOME MATERIALS BY DISCRETE IMPACT IN A BALLISTICS RANGE

The objective of this investigation was to demonstrate a valid technique for the study of threshold damage of materials by discrete impact, and to present results on some representative materials.

This work was conducted by the Missile Dynamics Division, Ballistics Department, of the Aero- & Hydroballistics Directorate of the Naval Ordnance Laboratory, Silver Spring, Maryland.

The program was supported by Code 035 of the Naval Ordnance Systems Command under Task Area Number UF 20322503, Work Unit Number ORD 35B-002-201-32.

Ceramic and control materials have been supplied by the Engineering Experiment Station of Georgia Institute of Technology. The assistance of Professor J. D. Walton, Jr., Chief, High Temperature Materials Division, with materials characterization and evaluation is greatly appreciated.

The electronic engineering and design contributed by Mr. A. Longas, NOL, White Oak, is gratefully acknowledged. Scanning electron microscope photographs were taken by Dr. M. Norr, Chemistry Research Department, NOL, White Oak.

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Commander

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By direction

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SYMBOLS AND ABBREVIATIONS

D_o	original diameter of spherical drops from drop generator
D_v	dimension of distorted drop in vertical direction
$\frac{m_s}{m_o}$	ratio of mass in partially stripped drop to its original mass
t_2	time from passage of shock wave over drop to impact with material specimen
T	nondimensional time to drop breakup or index of drop distortion
V_2	velocity imposed upon drop during time, t_2
ρ_2	air density surrounding drop during time, t_2
ρ_L	density of water drop
SCFS	slip cast fuzed silica ceramic material
SEM	scanning electron microscope

INTRODUCTION

Rain erosion on aircraft components has been recognized as a serious problem for many years. The problem of high-speed liquid impact can be traced back even earlier, however, to problems in turbine blade erosion.

More recently, the problem of rain erosion on missile materials in hypersonic flight has been the subject of accelerated investigations.

The primary objective of this report is the documentation of experimental methods and results on a study in progress in the Naval Ordnance Laboratory Aerophysics Ballistics Range. The first phase of this program was funded by ORD 035 of the Naval Ordnance Systems Command and is primarily directed towards the study of discrete impact of water droplets on ceramic radome materials.

The potential of discrete impact studies for supplying necessary information to fill gaps in the extremely complex pattern of impact and erosion damage, however, justifies a discussion of the general problem and background in addition to reporting results of the present program.

BACKGROUND

The background of effort in water drop and particle erosion is so extensive in some areas that a more detailed discussion and partial bibliography is included in Appendix A.

It is not possible to cover in the space permitted here a proper summary of the pertinent information contained in available references, but References (1) through (4) summarize the major findings and discuss most of the pressing and unresolved problems. References (5) and (6) present techniques for the study of certain problems in hypersonic rain erosion that have not been approached in most of the work done previously at transonic and supersonic velocities. Results of that work are being reported in classified reports and will not be discussed in this paper in order to keep present subject matter unclassified and to restrict it to velocities in the supersonic region or below.

The ultimate aim of erosion research is to find workable relations between "erosion rate" or the removal of material by successive water impact and the material and environmental factors involved in this material removal and damage. If a satisfactory understanding can be reached, and relations established that can be used with acceptable convenience, a twofold benefit should result. First, it should be possible to predict the response of a material in a known environment without subjecting it to expensive and tedious test evaluation. Second, and possibly more important, it might be possible to develop and evaluate new materials and carefully specify the range of working environment in which they will exhibit satisfactory erosion resistance. As can be inferred from the last statement, it does not appear feasible at this time to expect to develop a single material or family of materials that will be "best" for all erosion applications.

As discussed by Heyman (Ref. (2)), it must first be determined what the true criteria are for "damage" and "erosion" since the rate does not seem constant nor the characteristics simple in many cases. It has been demonstrated that at some conditions many hundreds of impacts can appear to have no effect upon a material surface, while many thousands of impacts will effect upon that same surface noticable pitting and eventually gross destruction of the surface with large-scale mass removal. Thus, the fatigue and long-term effects in the erosion process cannot be ignored. In the single impact of a liquid droplet with a solid surface, however, although much theoretical and experimental information is available, even for the simpler cases the entire mechanism is not completely understood (Refs. (2), (4) and (7)). In the case of some of the new and more complex materials, the mechanism of drop impact and material response are mutually interacting and much additional study is needed.

Although the eventual evaluation of erosion rate in some materials may require knowledge of dynamic materials response, sometimes at elevated temperatures for thousands of cycles, the response threshold to cold, single and discrete impact may supply the much-needed insight into the impact process and material response that is required to explain present anomalies in many areas in this complex problem.

The small Aeroballistics Laboratory Range offers an almost unique capability to investigate discrete impact through a wide range of conditions within reasonable limits of expense and time.

The Whirling Arm Facility (Refs. (9) and (10)), the Rocket Test Sled (Ref. (8)), and the Large Hyperballistics Range (Refs. (5), (6) and (8)), all fill specific needs in certain areas of rain erosion.

The Whirling Arm Facility (Refs. (9) and (10)) is limited to velocities below approximately Mach 3 in the extreme, and much of the data from these facilities has been at lower Mach numbers. Specimens must be small samples of materials. This type facility is a good approach to fatigue and erosion-type environments, but is of greatest value for relative rating of materials for such conditions and generally does not provide a highly controlled study of single or discrete impact nor a close simulation of flight conditions.

The Rocket Test Sled (Ref. (8)) has found most frequent application at Mach numbers of approximately 4 and below, although this limit has been extended to slightly higher velocities in some cases. The Test Sled has been used extensively for relative rating of materials samples, but the knowledge of actual impact and water conditions is limited and one of its major advantages would appear to be the capability of testing true, full-scale hardware configurations. The Rocket Test Sled is limited to tests at one atmosphere ambient pressure.

The small Aeroballistics Range and the techniques described in the following sections of this report will not provide the fatigue information of the Whirling Arm nor the full-scale model capability of the Test Sled. The capability for highly controlled impact studies through a continuous range of velocities from subsonic to hypersonic is unique, however.

The information can be obtained very rapidly and relatively economically and for the study of new materials should be used for initial evaluation prior to testing in other facilities such as those discussed previously.

The discrete impact and materials response information with definition of damage thresholds is invaluable at this state of the art for an understanding of new materials and interpretation of results from fatigue and multiple impact facilities.

NOL, WHITE OAK, AEROPHYSICS RANGE FACILITY

The Naval Ordnance Laboratory at White Oak currently operates a 1000-Foot Hyperballistics Range Facility, a 300-Foot Pressurized Aeroballistics Range Facility and an Aerophysics Range Facility. The latter is the smallest and most flexible and was selected for these discrete impact studies because of its general suitability to the problem and its capability for firing a large number of shots rapidly and economically.

The basic facility is 300-feet long and can operate with light gas gun launchers through a velocity range up to 25,000 ft/sec. Ambient pressures from atmospheric to 100 microns can be obtained. Model sizes range from microspheres to .80" diameter specimens for some conditions. Advanced optical and electronic monitoring instrumentation is available.

EQUIPMENT AND TEST CONDITIONS FOR DISCRETE IMPACT INVESTIGATIONS

The first phase of the present program was carried out with the supplementary apparatus indicated in the sketch of Figure 1. In this case a short-coupled arrangement utilizing a 20mm powder gun was employed. Some control materials such as "plexiglass" and "lexan" exhibit surface softening with extensive aerodynamic heating. A short flight path was necessary, therefore, to accomplish controlled firings with these materials. Approximately five feet beyond the launcher a rain or water drop generator (Fig. 2) was located. Immediately following particle impact, a velocity screen installation recorded specimen velocity, and the specimen was then captured in flexible foam. In the tests with solid particles, the particles are suspended in the same location as indicated for the drop generator. In order to evaluate initial drop size and to observe drop trajectory and condition just prior to impact, a photographic monitoring system (not shown in Fig. 1) is employed at the generator station.

Water Drop Generator

The theoretical basis for the design of a water drop generator was obtained from References (11) and (12). That literature describes the relationship between the liquid velocity through a short tube and the driving frequency necessary to achieve precise breakup into drops of uniform size and spacing. The proper combination of jet velocity and vibration of the fluid or the tube will, within limits, produce regular drops as indicated by the equations of the references. There is a spontaneous or natural instability and breakup at flow rates above the minimum, but results are not uniform and regular.

Glass capillary tubing was used for the tube in this application in place of the more troublesome hypodermic tubing. Less choice of internal diameter is available with capillary tubing but the target drop diameter of 1mm was closely approached ($\simeq$1.2mm) with tubing of .6mm internal diameter in the system shown in Figure 2a.

The water reservoir (1) is elevated by the jacking screw to permit sensitive adjustment of the water pressure at the injector head (4). Oscillations are induced in the injector by a rigidly mounted choke coil driven by a small solid-state oscillator. The choke acts on a piece of transformer lamination rigidly attached at one end and supporting the tube at the other end. The resilient pad provides the spring forces. An ordinary monaural phonograph pickup cartridge and needle (5) were found necessary in the shakedown of the drop generator system to monitor driving wave forms and frequencies. A separately driven stroboscope permits visual observation of the droplet distribution.

The present program called for nominal drop diameters of 1mm. In-house efforts are in progress to provide injectors for other drop sizes for follow-on efforts.

Photographic Monitoring Equipment

A low-power CW helium-neon laser beam was directed across the model flight path at a point slightly up-range of the water droplet stream. When the beam was interrupted by the model, a pulse was generated which triggered a high-voltage spark gap light source in a low-sensitivity parallel beam schlieren system. The photographs obtained from this system were used to observe drop size and shape prior to drop-model collision.

Model Capture Technique

Evaluation of model damage due to water drop impact requires retrieval of the model by a technique that contributes little or no damage to the model surface. Tests with different catching materials led to the selection of low-density flexible polyurethane foam squares of one- or two-inch thickness stacked so as to provide a continuous retardation medium about six feet in length.

The range of velocities required for each material was not known at the beginning of the investigation and it was necessary to carry out a rapid evaluation of catching techniques in order to start the program.

A first estimate of the upper velocities for this phase of the program gave a value of approximately 4,000 feet per second and preliminary firings were conducted on SCFS and Plexiglas through this range of velocities. Except for some small chipping of the edges of the specimen at the upper limit of velocity, no damage due to catching was visible on the SCFS and other ceramics tested.

Plexiglas showed some roughening of the surface at the upper velocities, but no damage due to catching was observed in the range of velocities of interest for this material ($<2,500$ ft/sec) and the technique was considered adequate for the present investigation.

Refinement of the present catching technique appears feasible if an increased range of velocities is required for the more damage-resistant materials in follow-on investigations.

Subsequent data firings as reported under Results have since confirmed the adequacy of the catching technique.

Material Specimens and Sabot Design

The material samples used in this investigation were supplied as 1/2-inch diameter wafers of 1/2-inch thickness.

The impact of one or two separately spaced 1mm water drops near the center on these samples was considered by the Materials Development personnel of Georgia Institute of Technology Experiment Station to properly represent discrete impact damage areas in the materials studied in this phase of the program. Impacts near the edge of a specimen were not used for data evaluation in a series fired for discrete impact threshold definition.

These specimens were pressed with a gentle press fit into cylindrical sabots of low-density polyethylene. Earlier sabots were approximately .80 inch in diameter and .80 inch long with each specimen custom fitted to its sabot. Later sabots were of similar dimensions but contained an O-ring on the aft portion of the cylinder to improve launch performance.

The damage photographs and data photographs in the figures illustrate the appearance of the model-sabot combination in flight and after capture.

LOW-PRESSURE INVESTIGATIONS

The original task plan for this program called for investigations at lower ambient pressures. The apparatus for the configuration shown in Figure 3 was designed and fabricated in response to this requirement. In multiple impact with some materials the aeromechanical damage mechanism and the degree of interaction of damage debris with flow fields and impacting particles depend upon the value of the ambient pressure (Refs. (5) and (6)). In the lower supersonic velocity range of this investigation of discrete impact, although the effect of wide differences in ambient pressure on the material removed cannot be assumed negligible for all materials, it may well be an indirect or second-order effect.

The effect of pressure on drop breakup and distortion is discussed later in this report. These effects involve more than the single parameter of ambient pressure, however, and depend strongly upon configurational and operational factors in actual application.

In view of these considerations, it was decided to concentrate effort in this program phase on normal impacts at one atmosphere ambient pressure. Follow-on work at reduced pressures can be carried out readily when required with the experimental configuration of Figure 3.

The basic approach used for this phase of the program is easily modified when it is required to accelerate solid particles into a target specimen. In this alternate technique the specimen is held stationary at the approximate location of the catcher in the present test setup, and the velocity of the launched particle or particles is measured just before impact. Variation of specimen temperature and impact angle is more easily accomplished with this technique.

In the firings with lead spheres in this program, the lead pellet was held on thin filaments of Duco cement in the same location occupied by the water drop column in the water impact tests.

DATA REDUCTION AND DAMAGE EVALUATION

In large-scale or gross damage and erosion it is reasonable to examine the surface for damage characteristics and to obtain by weight measurements or other means the mass of material removed. Such an evaluation results in a characterization of damage sites and will supply values and relative values of mass loss ratios, erosion rates and other evaluation parameters which can be used to predict flight damage and rank materials for erosion resistance.

The present study is not intended to provide this very necessary design information, nor will the need for systematic testing in whirling-arm type facilities be supplanted by discrete impact studies. What is attempted in this investigation is to carry out highly controlled discrete impacts and to record and observe the effects of these impacts with sufficient precision to provide specimens for advanced evaluation. The relation of early discrete damage thresholds to velocity and particle size and characteristics are also indicated with this technique. The potential for detailed evaluation of material characteristics in the damage sites for threshold impacts should, however, be pointed out at this time. The data reduction and preliminary evaluation described below is limited by program size and scope, but, further, more thorough evaluation may be profitable on the captured specimens at a later date.

Minimum Evaluation Procedure (Basic Data Recording)

In the present program phase, evaluation was limited for most specimens to direct visual inspection, observation with low-power optical magnification and surface examination under oblique or grazing light. Data for typical rounds are indicated in Appendix B. Figure 4 is an example of heavy damage on SCFS specimens.

Scanning Electron Microscope (SEM)

The scanning electron microscope has proven very useful in the detailed evaluation of damage mechanisms in materials. The extremely wide range of depth of field compared to optical microscopes gives it a great advantage (Fig. 5). NOL has a highly competent team in materials study who regularly employ the scanning electron microscope. A sample set of photographs were taken to characterize the slip cast fuzed silica in this program.

The SEM was not employed to evaluate general data specimens and impact areas during this program because of program limitations and the nature of the materials studied in the preliminary phase. This instrument should be of much greater value, however, as a diagnostic tool in composite and reinforced materials damage studies.

Figures 6 through 16 are included to demonstrate the characteristics of slip cast fuzed silica as viewed with the SEM. It can be seen from these examples that the limited damage areas studied exhibited the characteristics of simple fracture in the damage sites. This is demonstrated in Figures 7, 13, and 16, when compared with Figure 8.

DROP DISTORTION AND BREAKUP

It has been established for many years that in some cases of flight in actual rain environments the action of shock waves, flow fields and shock layers upon the incoming raindrops results in disintegration of the drop to the degree that no sensible damage is inflicted by water impact.

A very impressive and valuable background of theoretical and experimental effort has been carried out in this field. New contributions are continually being made. The results of References (13) and (14) for the lower Mach number regime and Reference (4) for high Mach number strong shocks are representative of the present knowledge of analytical estimation of drop distortion and breakup.

In evaluating or predicting water impact damage in any flight situation, it is important to investigate the water droplet environment and consider the drop trajectories and flow conditions from free stream to impact in a given area on the actual configuration. Obviously, the enterprising designer will take every advantage of drop breakup phenomena to reduce and eliminate water damage.

In many cases of experimental simulation, however, the drop distortion or breakup is minimal or nonexistent because of small standoff distance or other factors and it is reasonable to consider that impact between a spherical drop and the specimen surface represents a true physical model of the phenomenon.

In the present investigation, which extended over a rather wide range of conditions for several materials, drop disintegration does not appear to present a serious problem, but the effect of drop distortion and initial stripping of some drop mass must be evaluated to truly represent impact conditions.

An important consideration in the present technique is that impact conditions have been continually monitored photographically, as well as estimated analytically. This prevents the generation of questionable data where impact or water conditions are unusual or to some extent unknown, which, unfortunately, is the case in some of the past test data on water impact.

The present discussion will be limited to a general description of the problem with an attempt to identify the phenomenon as it affects the results of discrete impact research.

Engel, in work with a shocktube at NOL, White Oak, worked in the low supersonic Mach number region of interest in the present study (Ref. (13)).

In the range of velocity of Mach numbers from 1 to 2 with drop diameters of 1.4mm her results indicate that in order to experience drop disintegration, a standoff distance of several inches would be required. In most of the present investigation, this distance is less than an inch.

Four classifications or types of drop phenomena are of importance in high-speed droplet impact.

Drop Distortion
Drop Stripping
Drop Breakup by the Stripping Mode
Drop Breakup by the Catastrophic Mode

In impact experiments of the type reported here, the last two phenomena can be safely disregarded for any but exceptional cases.

It also appears that in many cases the first two will be insignificant in effect. In order to describe precisely the nature of the droplet impacting the specimen, however, it is important in a proper experiment to monitor and/or predict the extent of the first two effects, distortion and stripping, in the event that they reach values great enough to influence the damage mechanism.

It might be added at this time that in almost any conceivable impact situation in whirling arm and sled testing, there will be some degree of drop distortion and stripping.

To date there have been efforts to correlate drop distortion and stripping by several parameters; Weber number, "mixed" Reynolds number and others.

The present discussion will be limited to some simplified correlations of experimental data which give a means of predicting the extent of these effects in the flight case.

Reinecke, et al, have reduced several of the data to the parameter of a dimensionless time, T.

This dimensionless time can be utilized to obtain reference numbers with which one can predict the extent of drop breakup, drop distortion, and drop stripping based upon correlations with experimental results.

$$T = \frac{t_2 U_2}{D_o} \sqrt{\frac{\rho_2}{\rho_L}} \qquad (1)$$

T = Dimensionless Time
t_2 = Time Drop is Exposed to Distorting and Stripping Velocity
U_2 = Velocity Imposed on the Drop*
ρ_2 = Air Density Imposed on the Drop*
ρ_L = Liquid Density of the Drop
D_o = Diameter of the Drop Before Shock Passage

It can be appreciated that in the flight case the drop trajectories must be examined in detail for a truly representative result and drop accelerations, variations in U_2, ρ_2 and D_o should all be considered in a strictly quantitative evaluation. This is at best a complex and time-consuming computation and unless no other means will provide information on impact conditions, it is not usually justified in a materials evaluation. In the present case, a valuable estimate of degree of distortion and stripping can be made with some simple applications of Equation (1) used in conjunction with observed conditions from the monitoring photographs taken before impact.

The direct effect of ambient pressure in Equation (1) is reflected in the density term, ρ_2, and this effect is a square root effect as opposed to the effect of velocity, U_2, stay time, t_2, and the reciprocal of initial drop diameter, $1/D_o$. In the evaluation of ambient pressure on the discrete impact damage mechanism, the effect of all these parameters on the droplet should receive consideration, as well as the response of the material alone to pressure differences under identical conditions of impact.

The results of observations of drop breakup by the stripping mode indicate (Refs. (4) and (14)) that a reasonable approximation for conditions in the present program is to consider a dimensionless time value of $T = 3.5$ as representative of breakup by the stripping mode.

The conditions under investigation in the present study are approximately one order of magnitude below this ($T \simeq .2$ to $.4$) for the simple applications of Equation (1).

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* In the simple case these are velocity and density behind the advancing shock.

A summary of drop distortion results of several investigators at approximately Mach 3 and above is indicated in the envelope of Figure 17 based upon Reference (4) and the results of Ranger and Nicholls. The range of these data is for higher Mach numbers, but the upper boundary of the envelope provides a guide for estimating the results of the present experiment.

Several photographs of drop characteristics for a range of flight conditions are shown in Figures 18, 19 and 20. Earlier studies (Refs. (13) and (14)) have shown that the drops tend to expand perpendicular to the direction of flow velocity and develop a blunted spherical shape on the windward side and a flattening on the lee side. As the flow around the drop continues there appears at the periphery or meridian a stripping of mist or fine droplets. The optical methods are no longer very valuable in determining drop mass once this fog is present, since even a small percentage of drop mass in the form of mist or fog can appear opaque on the optical record. This was well demonstrated at high Mach numbers in Reference (4) where shadowgraph photographic analysis was compared with X-ray studies in the form of isophotes from radiograms. On the basis of such knowledge, the configurations of drops just about to impact the specimen, as shown in Figures 18 and 20, are interpreted to be in the very early stages of mass stripping.

The present program scope did not provide for firing several shots at each velocity to photograph the drops in many positions relative to the model face. It was necessary to combine the limited data obtained by routine monitoring with extrapolations and interpolations suggested by analysis to estimate drop conditions at impact over the entire range of velocities.

The shock generated by the sabot containing the specimen was often preceded by a weak shock from the gun blast. Experimental shock detachment distances were used, therefore, to fair a curve as indicated in Figure 21.

The standoff distances read from the curve were then used to determine values of t in Equation (1). Based upon these values of t and known values of D_o and ρ_L, two curves for dimensionless time, T, were calculated based upon the following assumptions.

In the first case, U_2 and ρ_2 were evaluated for conditions behind a normal shock travelling at sabot velocity. In the second case, stagnation conditions in front of the model were used to evaluate U_2 and ρ_2. Actual cases would be expected to lie between these curves shown in Figure 22.

Using the values indicated by the curves of Figure 22 and the results indicated in Figure 17, curves were plotted for the ratio of vertical drop diameter to original drop diameter. These results are indicated in Figure 23 and the range of observed values of D_v/D_o falls between the "theoretical" curves as expected. The vertical dimension of the drops can be measured more accurately on the schlieren photos than the horizontal dimension, but optical effects and vapor obviously cause some error.

The phenomena of distortion and stripping will certainly exhibit some lag or inertia effects in a rapidly changing flow environment and even a more rigorous trajectory evaluation would contain errors from such effects.

The estimates of Figure 23 for drop distortion at impact are, therefore, presented as being a reasonable representation of this parameter for the results of this investigation.

The interpretation of drop stripping is a more difficult undertaking, as discussed previously.

Reinecke gives an expression for estimation of mass removed due to stripping in the flight case.

The drop mass at impact in the stripping mode is estimated by the equation

$$\frac{m_s}{m_o} = \frac{1}{2}\left[1 + \cos \pi \frac{T}{3.5}\right] \qquad (2)$$

As an approximation of this parameter, the trend of experimental results from Figure 23 was used in obtaining values of T for use in Equation (2). The results of this maneuver, although lacking in physical basis, are somewhat justified by comparison with experimental work in shock tubes. The resulting estimates for mass remaining at impact are given in Figure 24. The curves of Figures 23 and 24 have been used to select values of drop distortion and stripping for each data shot.

This aspect of the present technique may be an asset rather than a disadvantage, since, as indicated previously, the flattened and partially stripped drop may represent the usual impact situation for material damage in most physical situations at the velocities of interest for radome materials.

At any rate, for the results of the present investigation, the conditions at impact are indicated for each data condition and impact area in the event that detailed evaluation of the impact process is attempted at a later date.

Impact Angle

The present phase of the program was confined to normal impact and high angle of yaw data are not presented.

An interesting auxiliary result is indicated in shots such as number 80, however, shown in Figure 4. As can be observed in Figure 20, the effect of the flow at the shoulder of the sabot is to cause drops near the outer edge of the sabot to approach at an angle. The impact areas in low-density polyethylene as seen on the sabot in Figure 4 show a definitely nonsymmetrical damage pattern which is probably due to the angle of impact.

Work at several impact angles is planned for follow-on effort to this program.

Estimated values of angle of yaw are listed in the data sheets, e.g., Appendix B.

RESULTS

Results of Phase I of this program are presented for the sponsor in the form indicated by the data sheets in Appendix B. Data are indicated in this appendix for the major materials and conditions of the preliminary program. In addition, the captured specimens for all firings are retained for additional evaluation or supplied to the sponsor with the data sheets, as desired.

Characterization sheets for materials used are found in Appendix C.

Typical results for the major part of this program phase (1mm water drop impact on slip cast fuzed silica) are summarized in Tables I and II.

The results of most of the work in Phase I are summarized in Figure 25.

The results on some materials are not included in this report.

The results in the third column of Figure 25 represent the data given in greater detail in the data sheets and Tables I and II. In impact of slip cast fuzed silica with water drops of nominally 1.2mm (.047") diameter, three damage thresholds can be detected.

Early damage is recognized at approximately 1200 to 1600 feet per second impact velocity, depending upon the characteristics of the material surface. This damage takes the form of very small surface pits. These pits do not appear in any apparent systematic location within the impact area.

A second threshold occurs between approximately 1800 and 2400 feet per second in which the pitted areas become circular in form and flat or uneven floored craters appear with increasing velocity

Above approximately 2400 to 2500 feet per second the craters take the form of classical impact craters with ringed depressions around their outer edge. This damage is heavier in nature and represents relatively heavy material loss compared to the early threshold.

There has been no effort in this phase of the investigation to study the detailed impact areas in order to attempt correlation of damage at different velocities with solid particles and water. However, preliminary results with two sizes of lead spheres are presented in columns 1 and 2 for comparison with water impact results with slip cast fuzed silica. At very low velocities with .050" lead spheres slight marking of the surface with no visible damage occurs. In the range from 200 to 500 feet per second lead deposits appear in the surface material. Incipient damage may be inflicted under these conditions, but the simple evaluation techniques used do not permit the measurement of such damage if it exists. Above 500 feet per second imbedded lead deposits and irregular craters start to appear.

In the series with .070" lead spheres, the early threshold was not determined. At very low velocities, 300 to 400 feet per second, imbedded deposits and craters appear, however, and within a small additional increase in velocity very heavy damage is sustained.

Several series of shots were run on Plexiglas* as a control material. The results in columns 4 and 5 of Figure 25 are representative of the results. The limited techniques for this phase of the investigation made evaluation of Plexiglas difficult. More detailed information could probably be obtained by more elaborate examination. Surface deformation appears at approximately 300 feet per second and imbedded lead deposits and craters are established by velocities above 600 feet per second. In water impact on Plexiglas the same early thresholds appear to form at two to three times the velocities encountered with the .050" lead spheres. Extensive subsurface cracks appear as velocity is increased above approximately 1000 feet per second.

Results with Corning 9606*, a pyroceramic-type material, were limited because of insufficient specimens, but are indicated in columns 6 and 7. Even at velocities of the order of 3500 feet per second no visible damage appeared with 1.2mm water drops.

A comparison of the results in columns 3 and 7 is very similar to earlier test sled results with an SCFS and Corning 9606* type materials.

CONCLUSIONS AND FUTURE WORK

Results of the type presented here should be necessary for all new materials and will be useful for background reference for any material in interpreting fatigue and multiple impact data.

*The use of trade names does not constitute Government endorsement or criticism of a material.

The small Aeroballistics Range has been shown to offer a rapid and controlled means for the investigation of discrete impact in radome materials.

Although certain fatigue mechanisms in some materials are not represented in these tests, discrete impact appears to be worthwhile and necessary to supplement whirling arm, rocket sled and other tests.

This is particularly important in the study and evaluation of new materials.

Distinct and significant damage thresholds have been demonstrated in ceramic materials by applying discrete impact techniques through a continuous range of velocity.

Present plans for FY72 include additional work with SCFS and other materials with water impact at other drop sizes, and solid impact through a range of velocities.

Impact at other than normal angle and at reduced pressure can be carried out where required.

The work with additional materials through a range of particle sizes as well as through a range of velocities should disclose trends and thresholds beyond the limited results of Phase I.

Some materials appear to show significant trends with particle size variation as well as with velocity. The relation of such parameters will be examined in FY72 programs.

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(14) Ranger, A. and Nicholls, J., "Aerodynamic Shattering of Liquid Drops," AIAA Journal, Vol. 7, No. 2, February 1969.

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TABLE I

SCFS (GEORGIA TECH LCT FROM JANUARY 1971) GROUP I

FIRST DATA SERIES, PRESSURE 760 TORR

INITIAL DROP DIAMETERS D_o = 1.2mm

ESTIMATES OF DROP DISTORTION, $D_v/D_o \cong 1.7-1.4$

ESTIMATES OF DROP STRIPPING, $m_s/m_o \cong .95-.98$

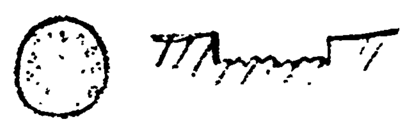
Shot Number	Velocity Ft/Sec	Est. Yaw	Comments, Minimal Evaluation Optical Magnification and Grazing Light
88	1700	3^o	Barely discernable ring approx. 1mm in diameter Slight pits on one edge 
81	1790	2^o	Similar to Shot 88 
87	1920	3^o	Area approx. 1mm in diameter showing shallow pitting in several spots 
86	1980	2^o	Area approx. 1mm in diameter on each of two impact sites, deeper general pitting over most of the area 
79	2120	3^o	Approx. 1mm in diameter site pitting deeper than Shot 86
78	2620	0^o	Approx. 1mm in diameter Definite uneven floor to crater 

TABLE I (CONT'D)

CONCLUSIONS AND RECOMMENDATIONS

1. True threshold appears to be below 1500 ft/sec. with this drop size.

2. Evaluation of damage sites and craters by more advanced methods of evaluation is recommended.

3. Initial damage, from visual examination, appears to take the form of fracture of small pieces out of the surface in random manner.

4. Three regimes of damage appear to exist based on this preliminary evaluation.

    a. Random small surface fracture
    b. General breaking out to form crater
    c. Crater with depressed ring at periphery

TABLE II

SCFS (GEORGIA TECH LOT INVOICE 3/25/71 GROUP VI)
SECOND DATA SERIES, 760 TORR
INITIAL DROP DIAMETER 1.1-1.2mm

$D_v/D_o \cong 1.8\text{-}1.4$

$m_s/m_o \cong .95\text{-}.98$

COMMENTS

The surface of this series of specimens was not as perfect as that of the first. Minute pits and very faint surface ridges and depressions were observed before firing.

This may have been responsible for shifting the first damage threshold (random pitting) downward to about 1400 ft/sec.

The remainder of the series at higher velocities behaved very similar to the first series, and is not repeated here.

Below 1200 ft/sec, no visible damage was observed. (See Figure 25 and Appendix B)

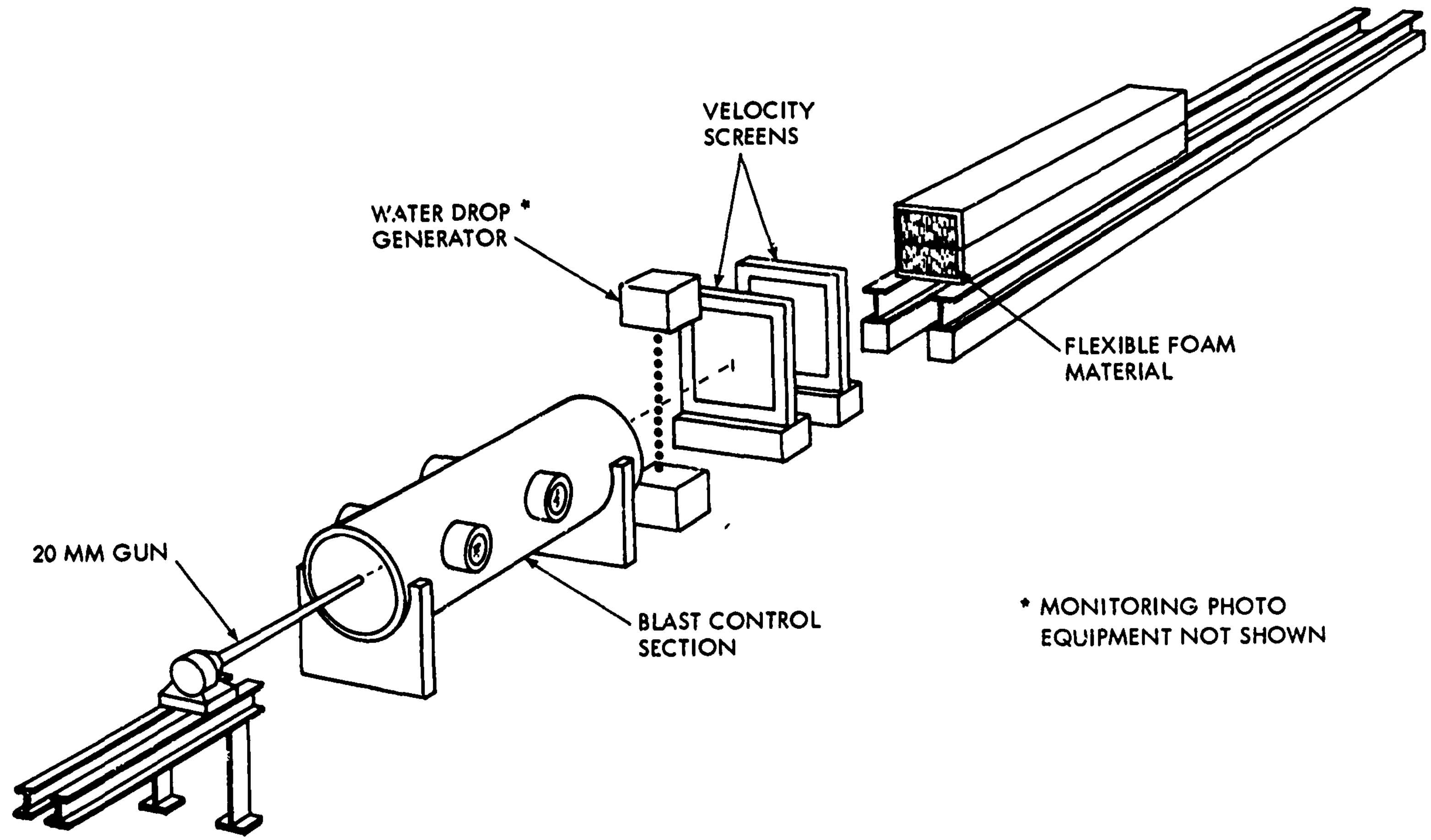
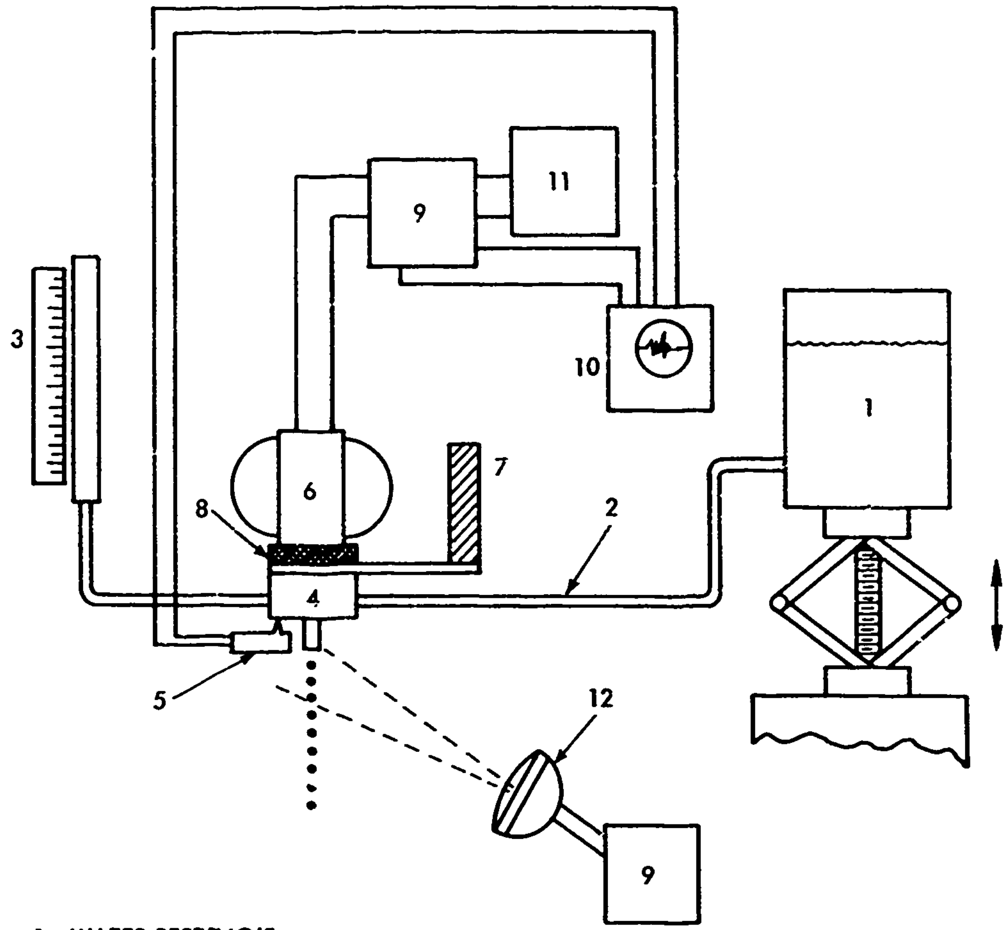


FIG. 1 ARRANGEMENT OF EXPERIMENTAL APPARATUS FOR DISCRETE IMPACT STUDIES IN THE AEROPHYSICS BALLISTIC RANGE (ATMOSPHERIC TESTS)



1 WATER RESERVOIR (ADJUSTABLE HEAD)
2 FLEXIBLE HOSE
3 MANOMETER
4 INJECTOR (CAPILLARY TUBE)
5 CRYSTAL PICK UP
6 CHOKE COIL
7 FRAME
8 RESILIENT PAD
9 OSCILLATORS
10 OSCILLOSCOPE
11 POWER SUPPLY
12 STROBOSCOPE

FIG. 2 (A) SCHEMATIC ARRANGEMENT OF WATER DROP GENERATOR

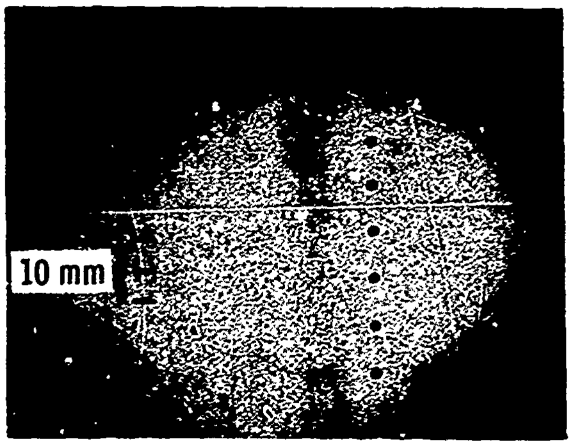


FIG. 2B TYPICAL DROP PATTERN FROM WATER DROP GENERATOR

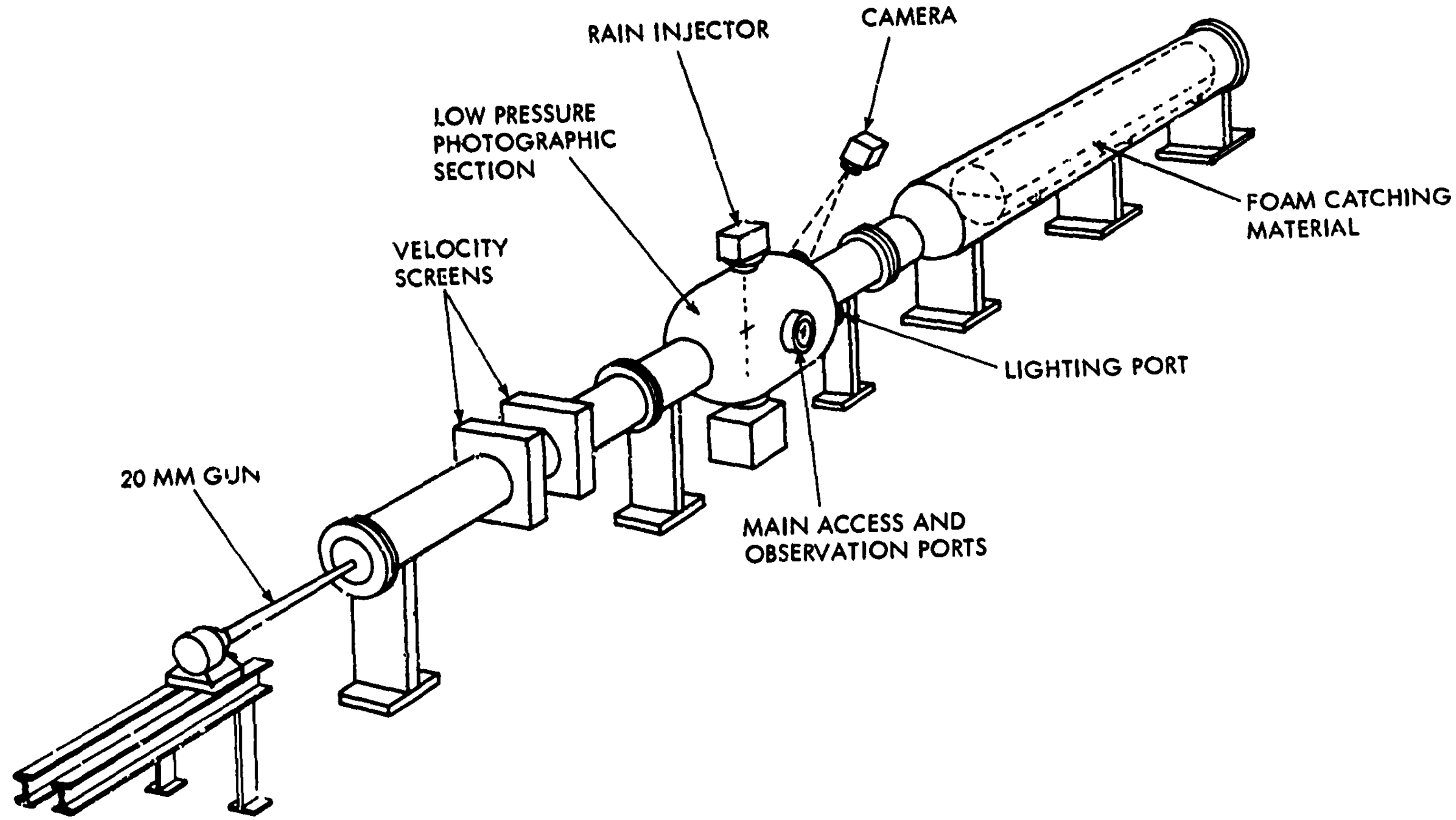
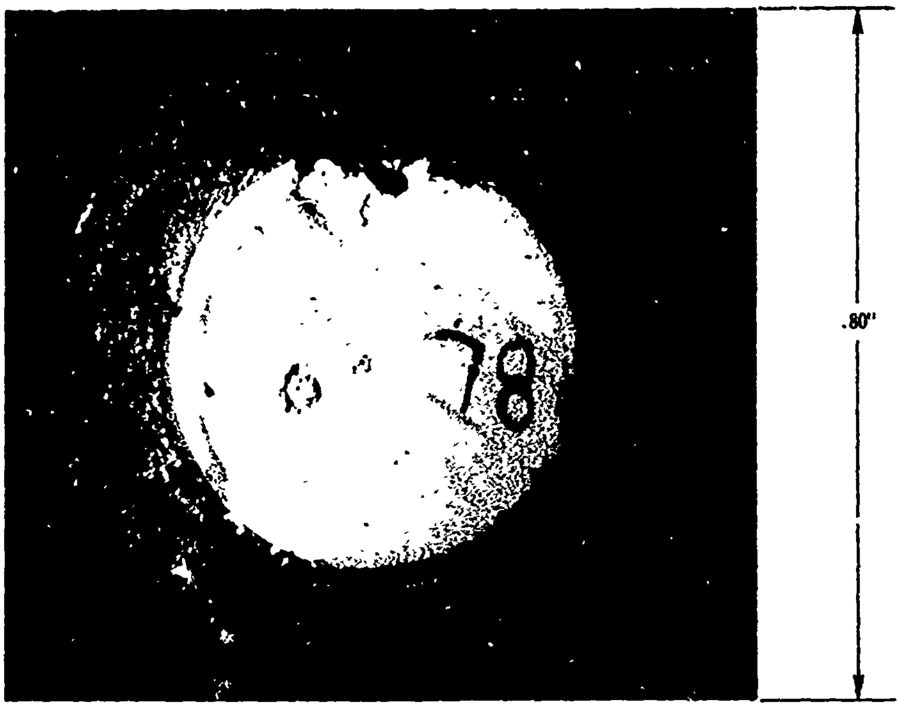
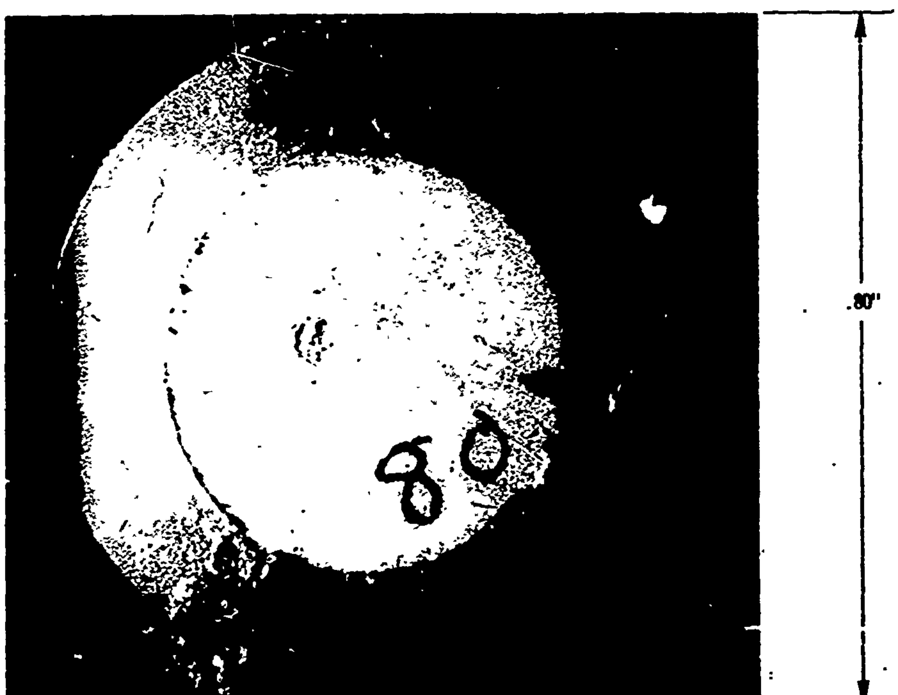


FIG. 3 PROPOSED EXPERIMENTAL APPARATUS FOR INVESTIGATION AT REDUCED PRESSURE

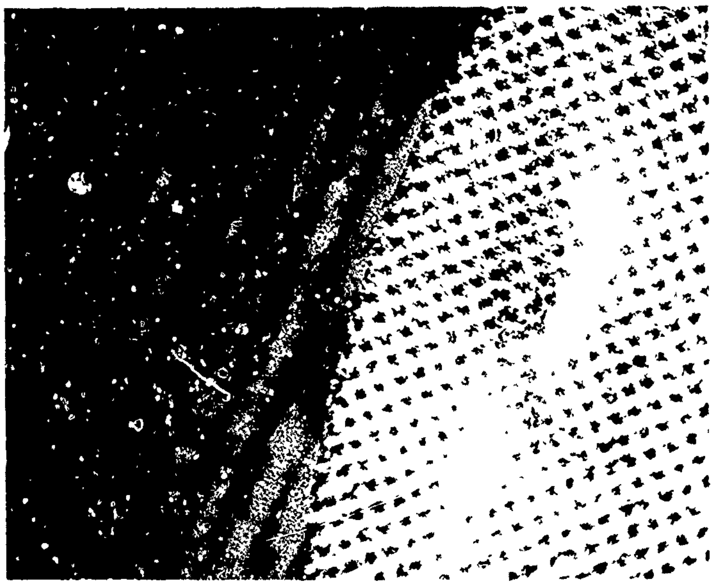


\# 78
760 TORR
2620 F/S
D_o = 1.2 MM WATER
SABOT MTRL. POLYETHYLENE (LOW DENSITY)

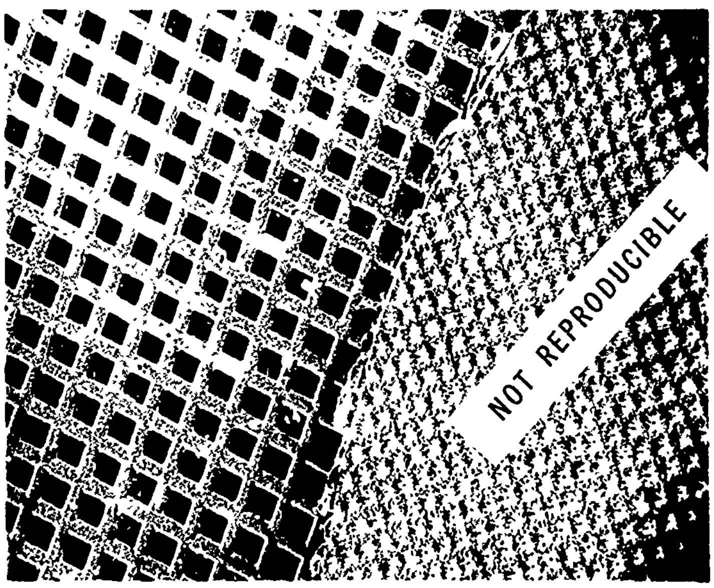


\# 80
760 TORR
2290 F/S
D_o = 1.2 MM WATER
SABOT MTRL. POLYETHYLENE (LOW DENSITY)

FIG. 4 IMPACT DAMAGE, SCFS SPECIMENS



OPTICAL MICROSCOPE
100 X MAGNIFICATION



SCANNING ELECTRON MICROSCOPE
100 X MAGNIFICATION

FIG. 5 EXAMPLE OF RELATIVE DEPTH OF FIELD CAPABILITIES
OF OPTICAL AND ELECTRON MICROSCOPES

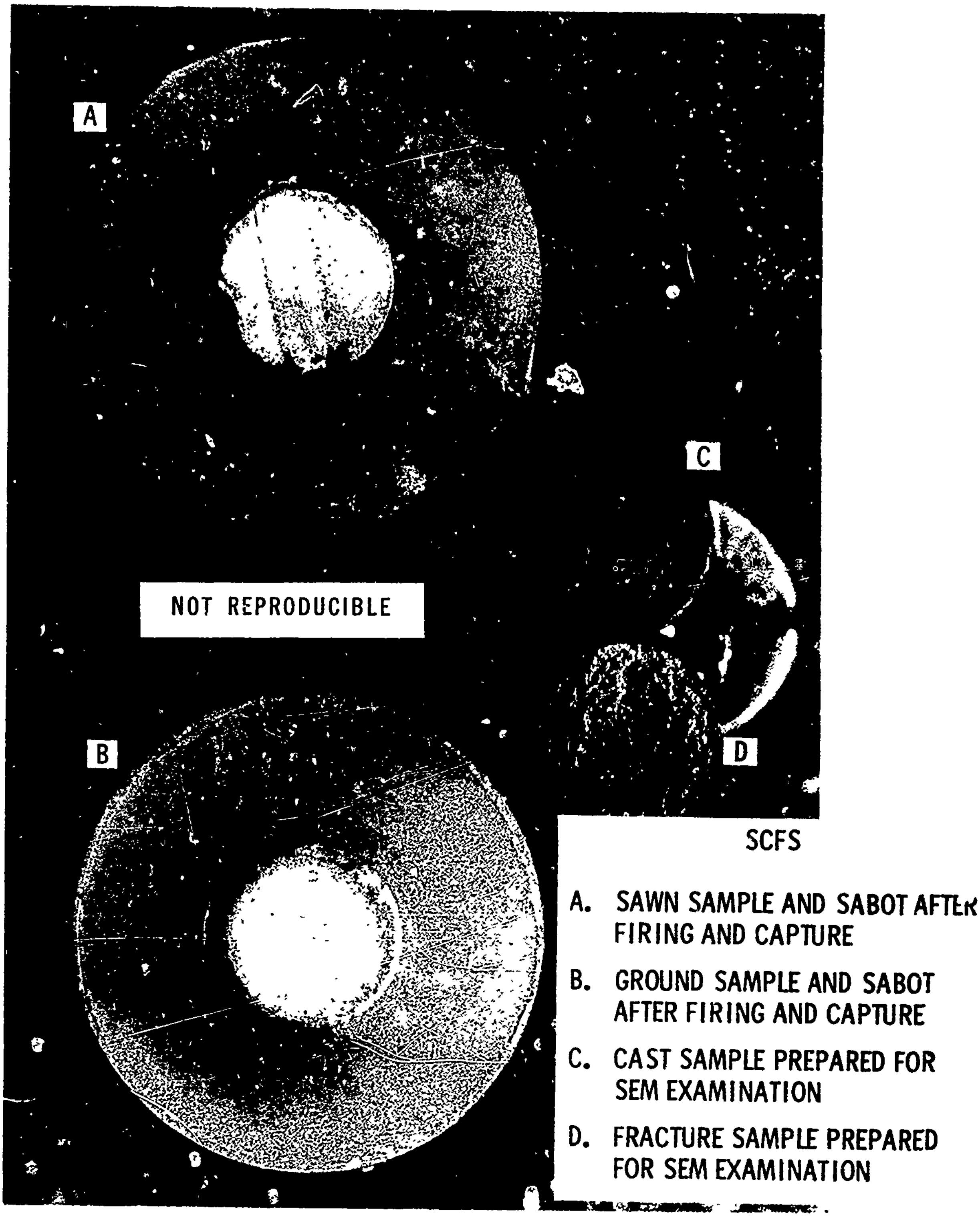
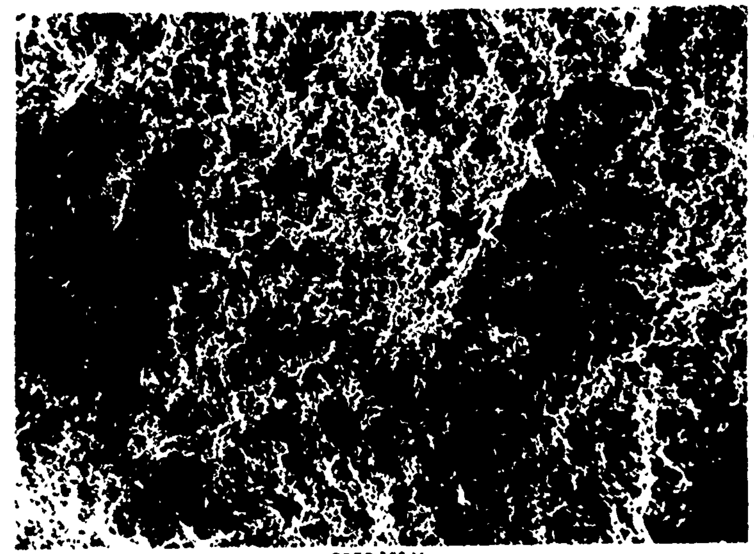
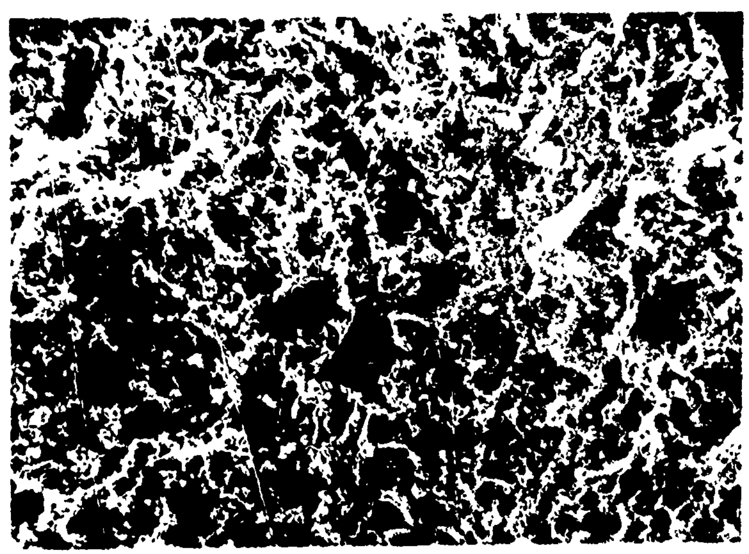


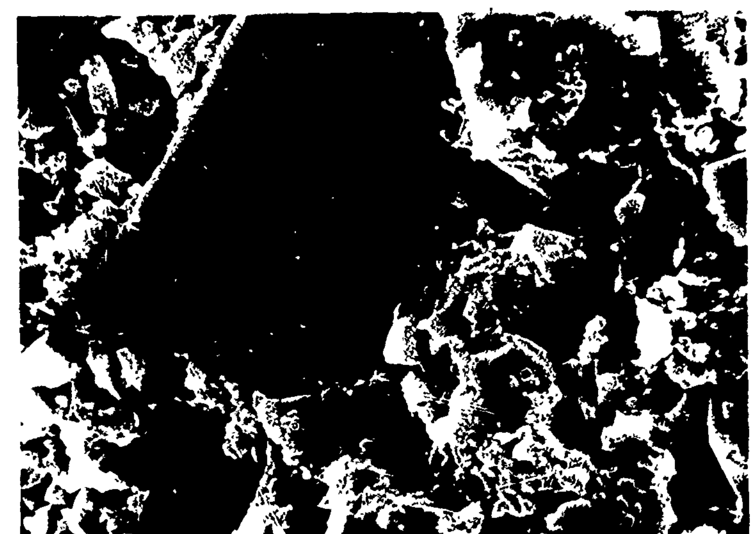
FIG. 6 TYPICAL CERAMIC MATERIAL SURFACES EXAMINED IN PRELIMINARY PROGRAM (1/4" DIAM. PRELIMINARY SAMPLES)



SCFS 100 X



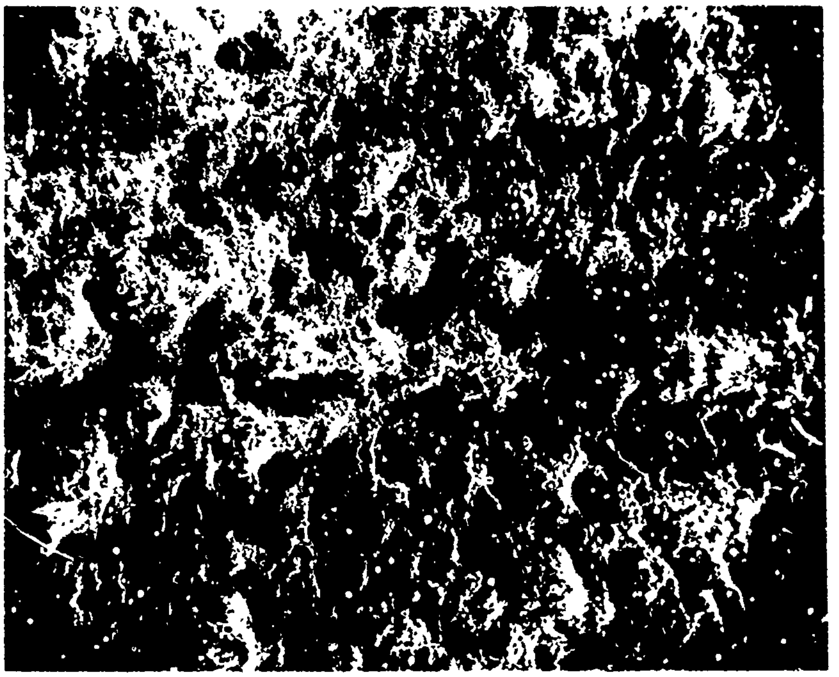
SCFS 500 X



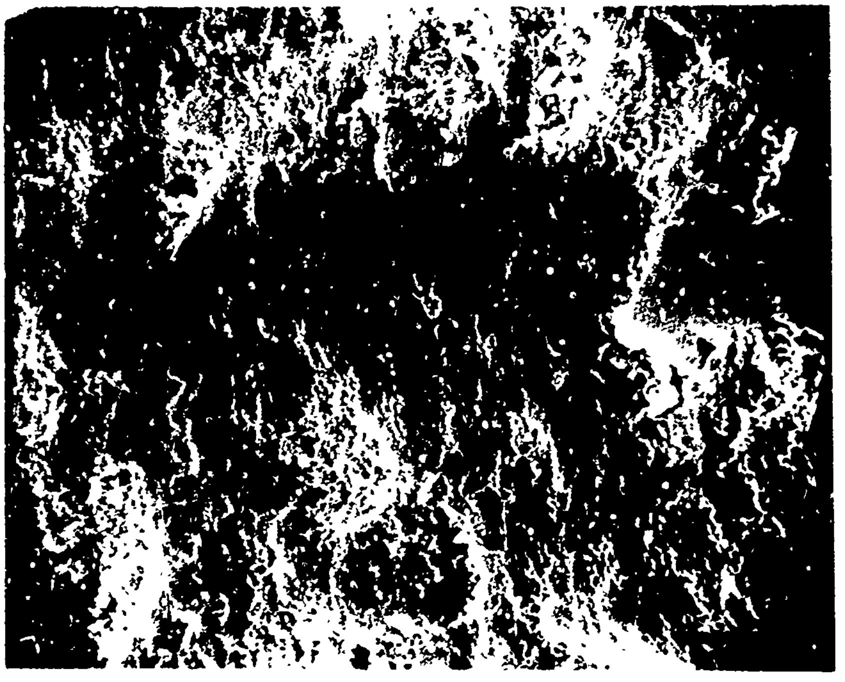
SCFS 2500 X

CHARACTERISTICS OF FRACTURE SURFACE

FIG. 7 SCANNING ELECTRON MICROSCOPE PHOTOGRAPHS OF SLIP CAST FUZED SILICA SAMPLE



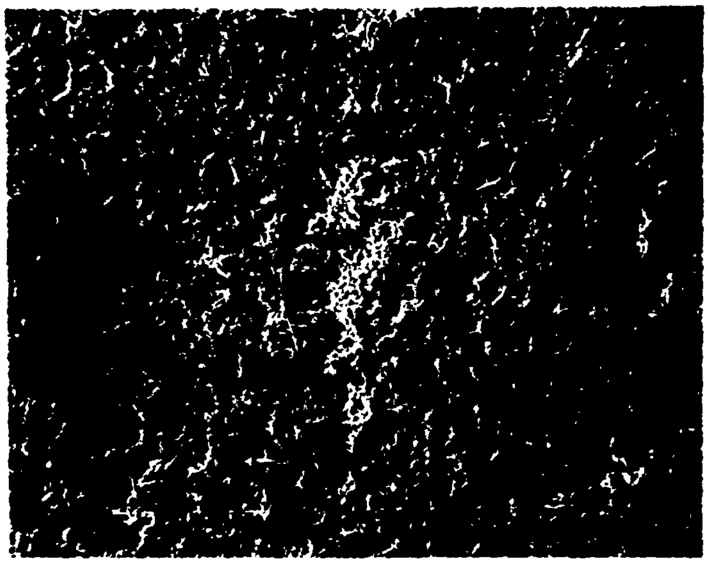
SCFS 500 X



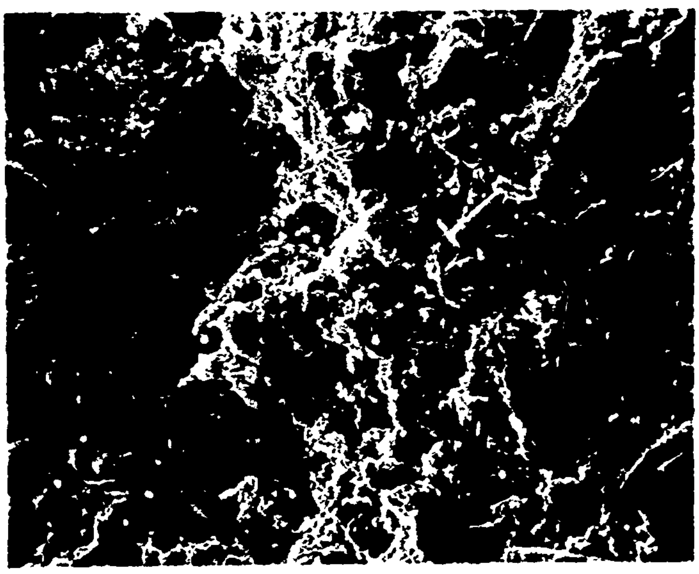
SCFS 2500 X

CHARACTERISTICS OF GROUND SURFACE

FIG. 8 SCANNING ELECTRON MICROSCOPE PHOTOGRAPHS OF SLIP CAST FUZED SILICA SAMPLE

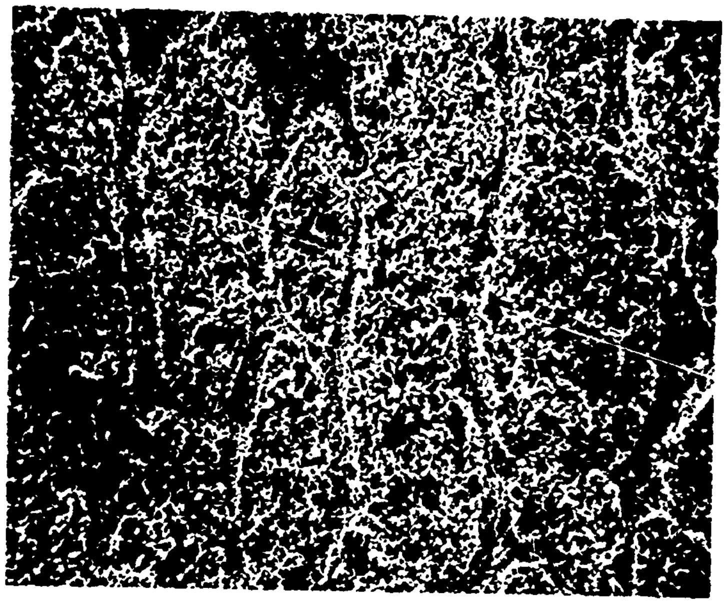


SCFS 100 X

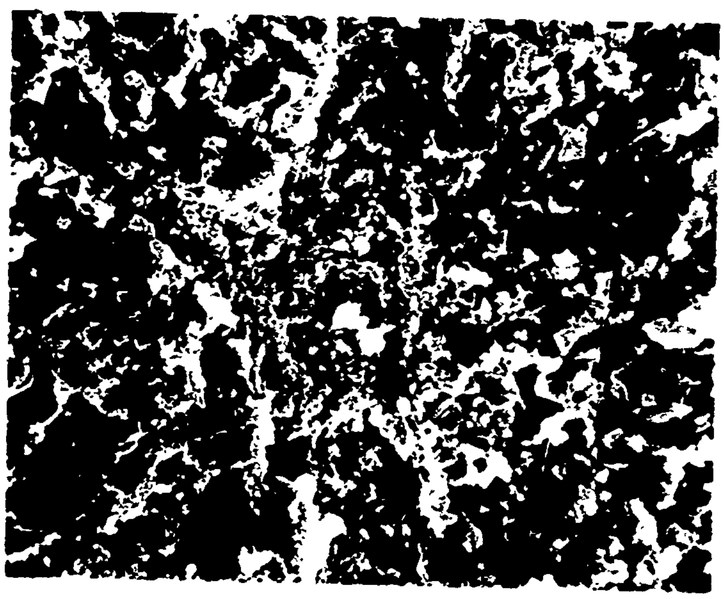


SCFS 500 X

FIG. 9 CHARACTERISTICS OF CAST AGAINST GLASS SURFACE

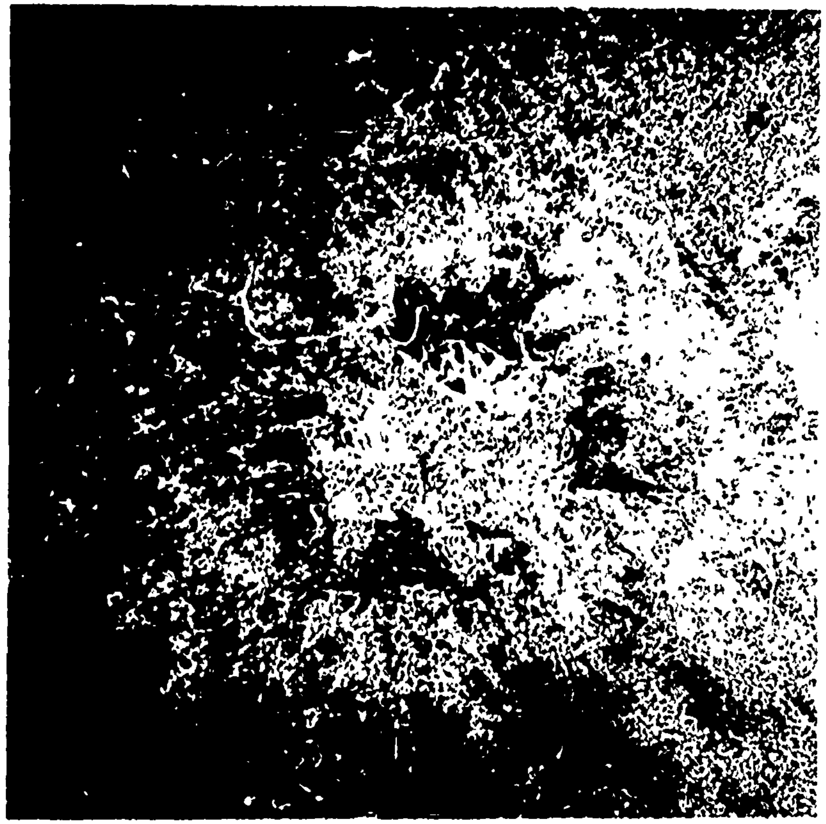


SCFS 250 X

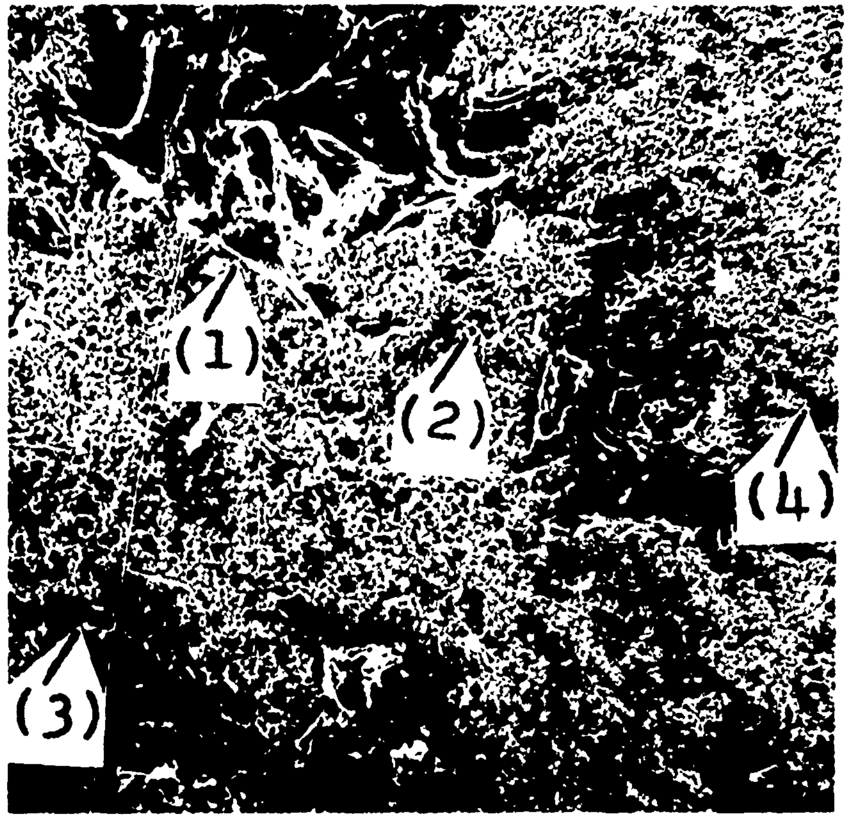


SCFS 1250 X

FIG. 10 CHARACTERISTICS OF CAST AGAINST PLASTER SURFACE



IMPACT LOCATION

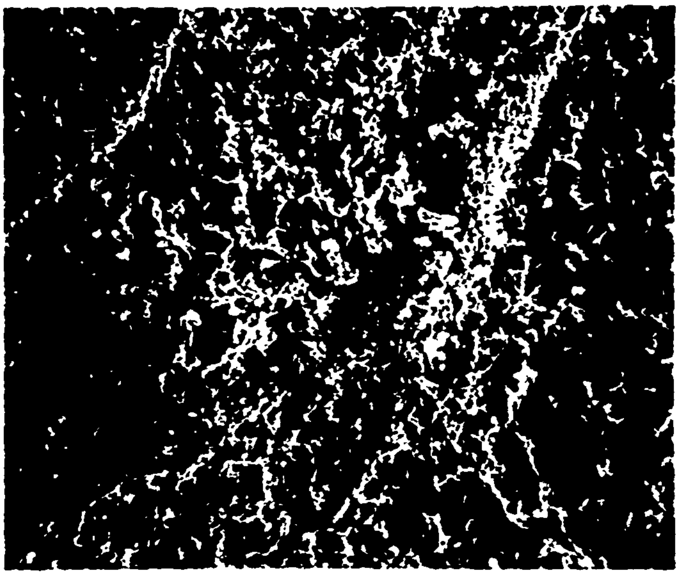


AREAS EXAMINED

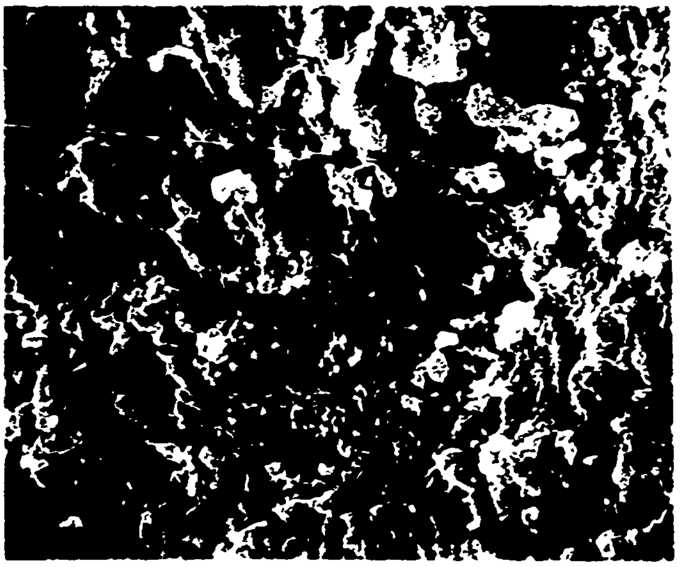
SLIP CAST FUZED SILICA SPECIMEN (CAST AGAINST PLASTER)
1/2" DIAM. x 1/2" THICK (DISC)
MOUNTED IN 0.8" DIAM. x 0.9" LEXAN SABOT
VELOCITY 668 FT/ SEC
IMPACTING NO. 9 CHILLED LEAD SHOT (0.070" DIAM.)

AREA 1 EDGE OF DAMAGE AREA
AREA 2 WITHIN DAMAGE AREA
AREA 3 EDGE OF DAMAGE AREA
AREA 4 UNDAMAGED AREA

FIG. 11 SCFS SPECIMEN FOR SEM EXAMINATION

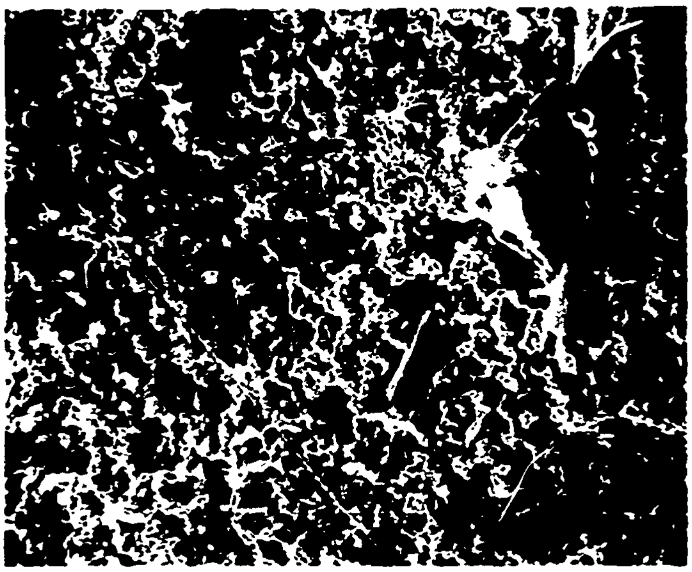


750 X SEM PHOTO

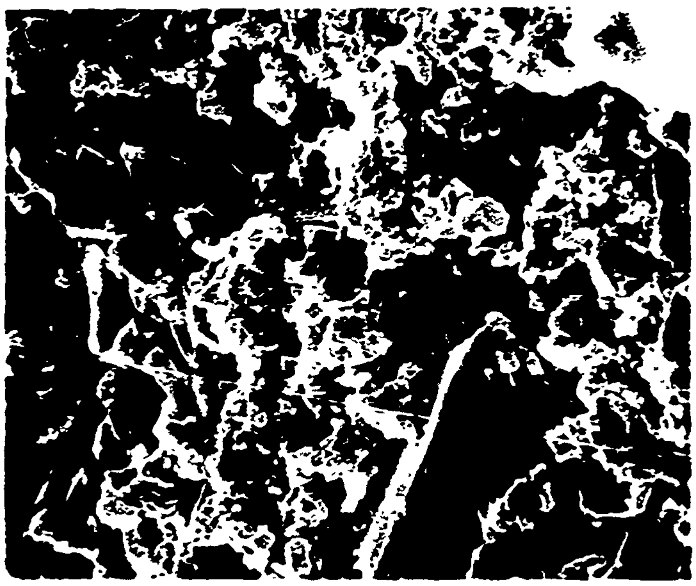


2000 X SEM PHOTO

FIG. 12 EXAMINATION OF UNDAMAGED AREA 4 FROM FIG. 11



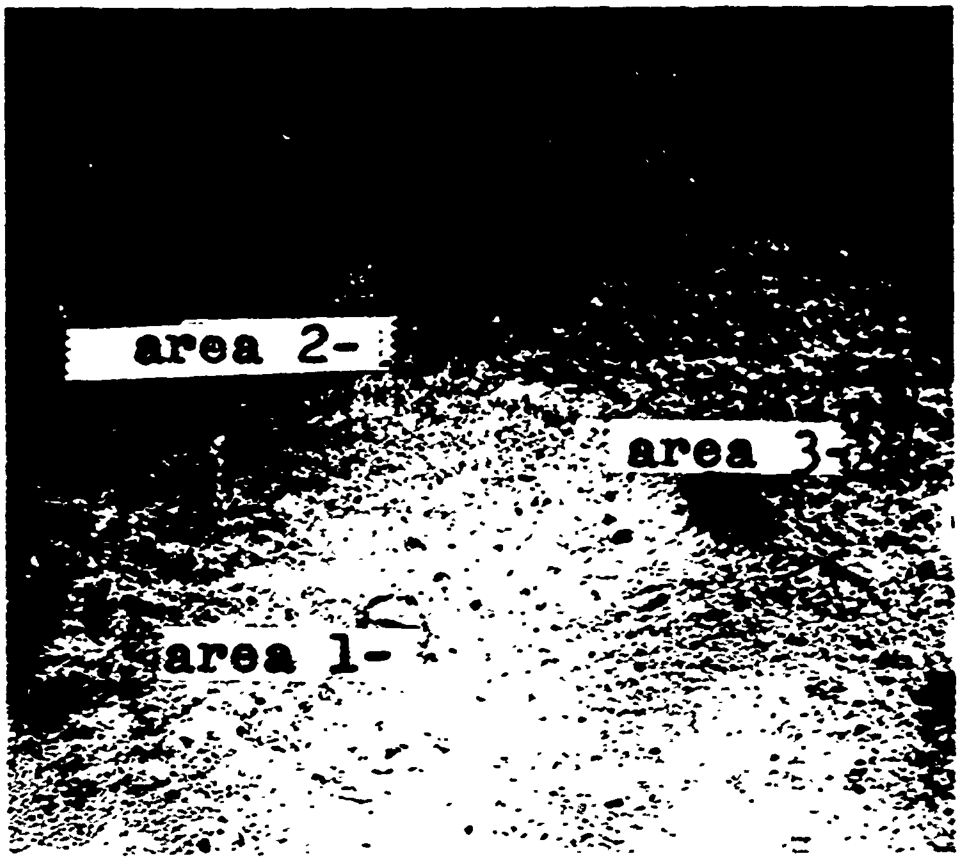
750 X SEM PHOTO



2000 X SEM PHOTO

FIG. 13 EXAMINATION OF DAMAGE AREA 2 FROM FIG. 11

NOT REPRODUCIBLE

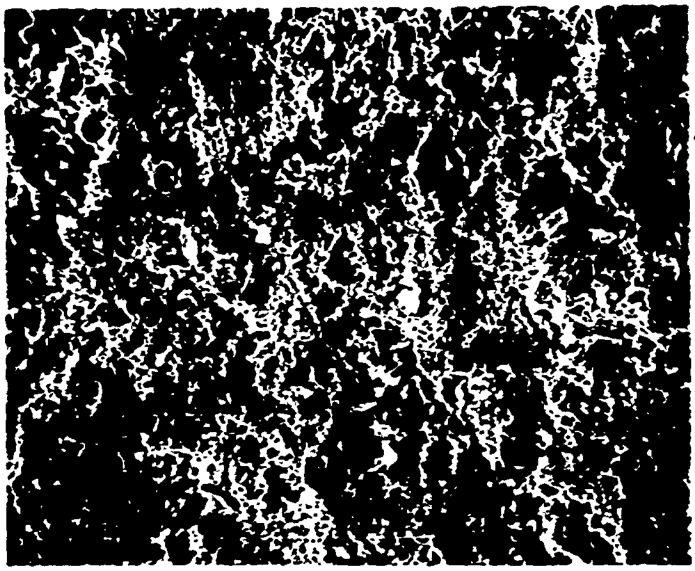


AREAS EXAMINED

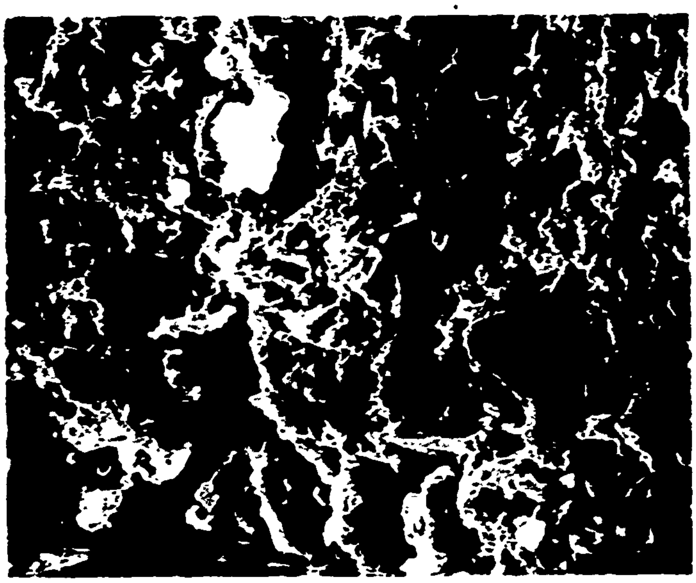
SLIP CAST FUZED SILICA SPECIMEN (CAST AGAINST GLASS)
1/2" DIAM. x 1/2" THICK (DISC)
MOUNTED IN 0.8" DIAM. x 0.9" LEXAN SABOT
VELOCITY 545 FT/SEC
IMPACTING NO. 9 CHILLED LEAD SHOT (0.070" DIAM.)

AREA 1 IMPACT DAMAGE AREA
AREA 2 EDGE OF IMPACT AREA
AREA 3 UNDAMAGED AREA

FIG. 14 SCFS SPECIMEN FOR SEM EXAMINATION

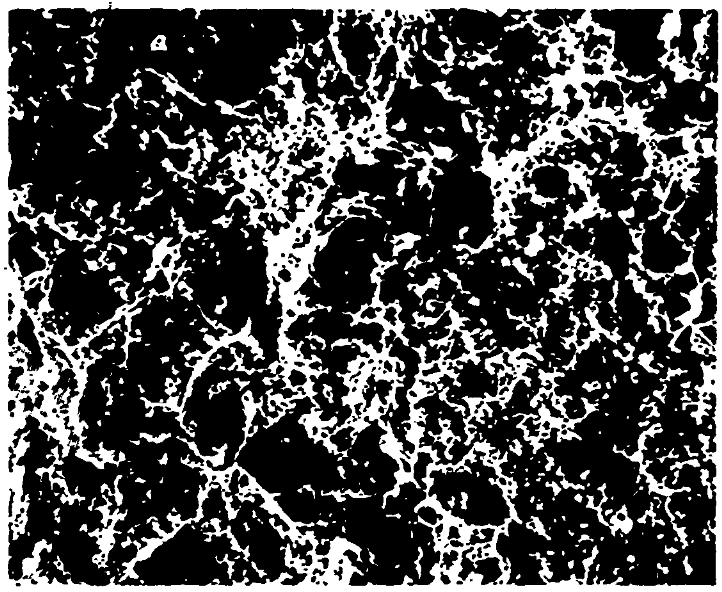


500 X SEM PHOTO

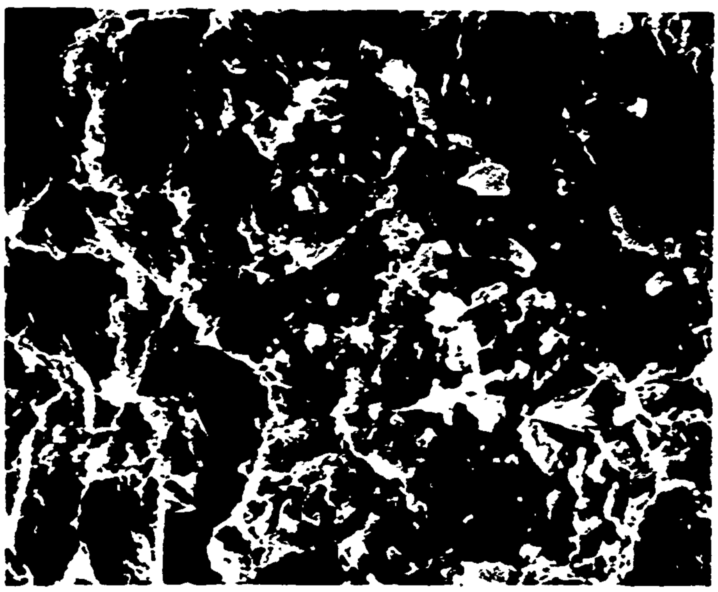


2000 X SEM PHOTO

FIG. 15 EXAMINATION OF UNDAMAGED AREA 3 FROM FIG. 14



500 X SEM PHOTO



2000 X SEM PHOTO

FIG. 16 EXAMINATION OF DAMAGE AREA 1 FROM FIG. 14

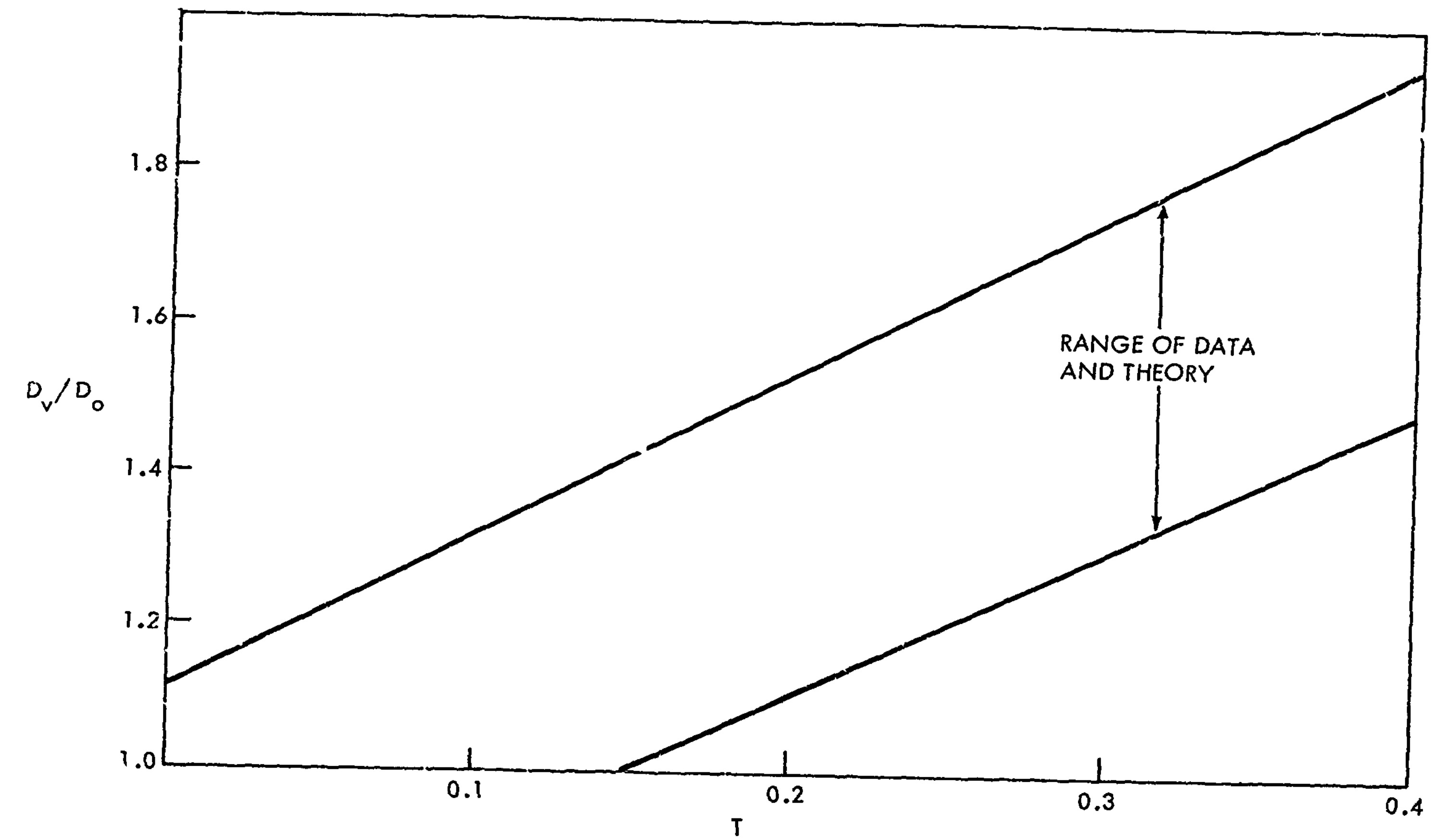


FIG. 17 EARLY TIME DROP DISTORTION (ENVELOPE OF THEORY AND DATA)

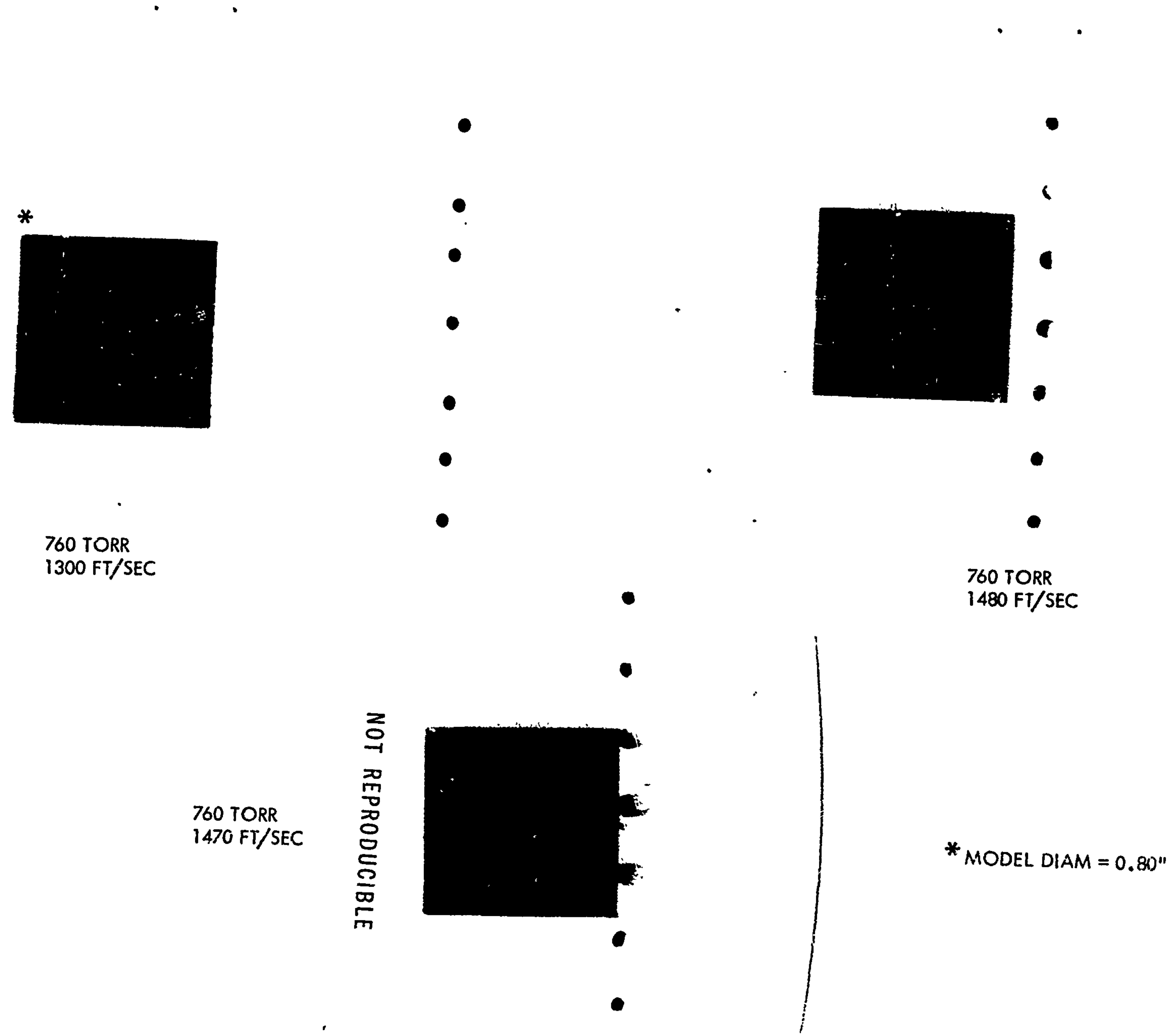


FIG. 18 EXAMPLE OF PHOTOGRAPHIC RECORDS OF DROP -MODEL IMPACT (JUST PRIOR TO IMPACT)

760 TORR
1380 FT/SEC

760 TORR
1390 FT/SEC

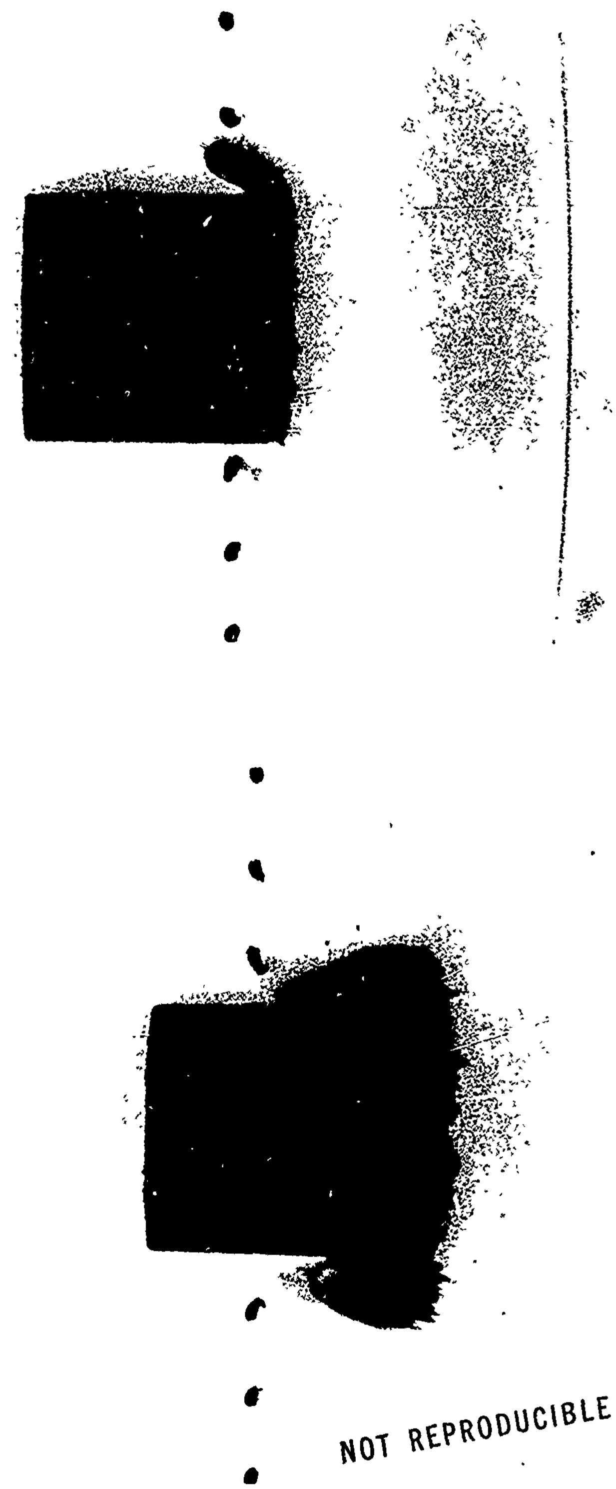
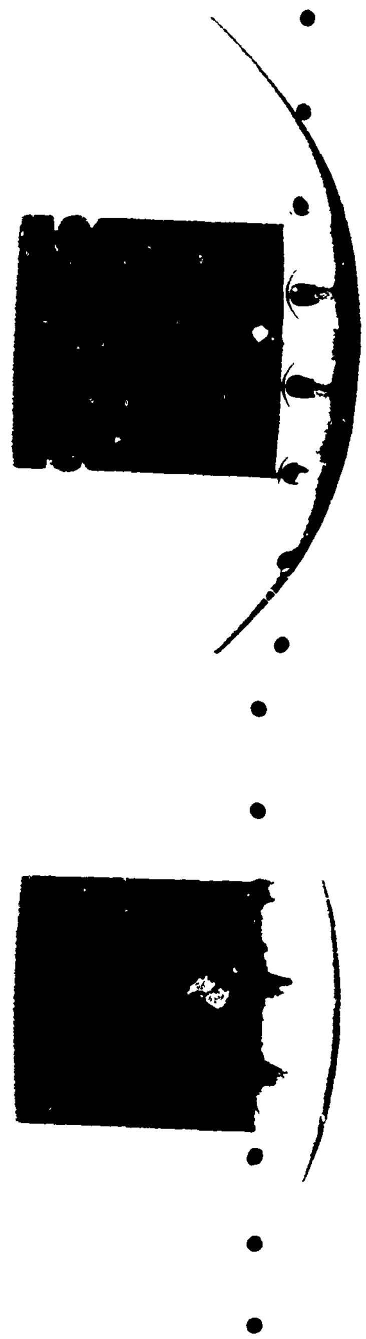


FIG. 19 CONDITIONS JUST AFTER DROP IMPACT



118
760 TORR
2970 F/S
D_0 = 1.12 MM

#78
760 TORR
2620 F/S
D_0 = 1.20 MM

NOT REPRODUCIBLE

FIG. 20 DROP DISTORTION PHOTOGRAPHS

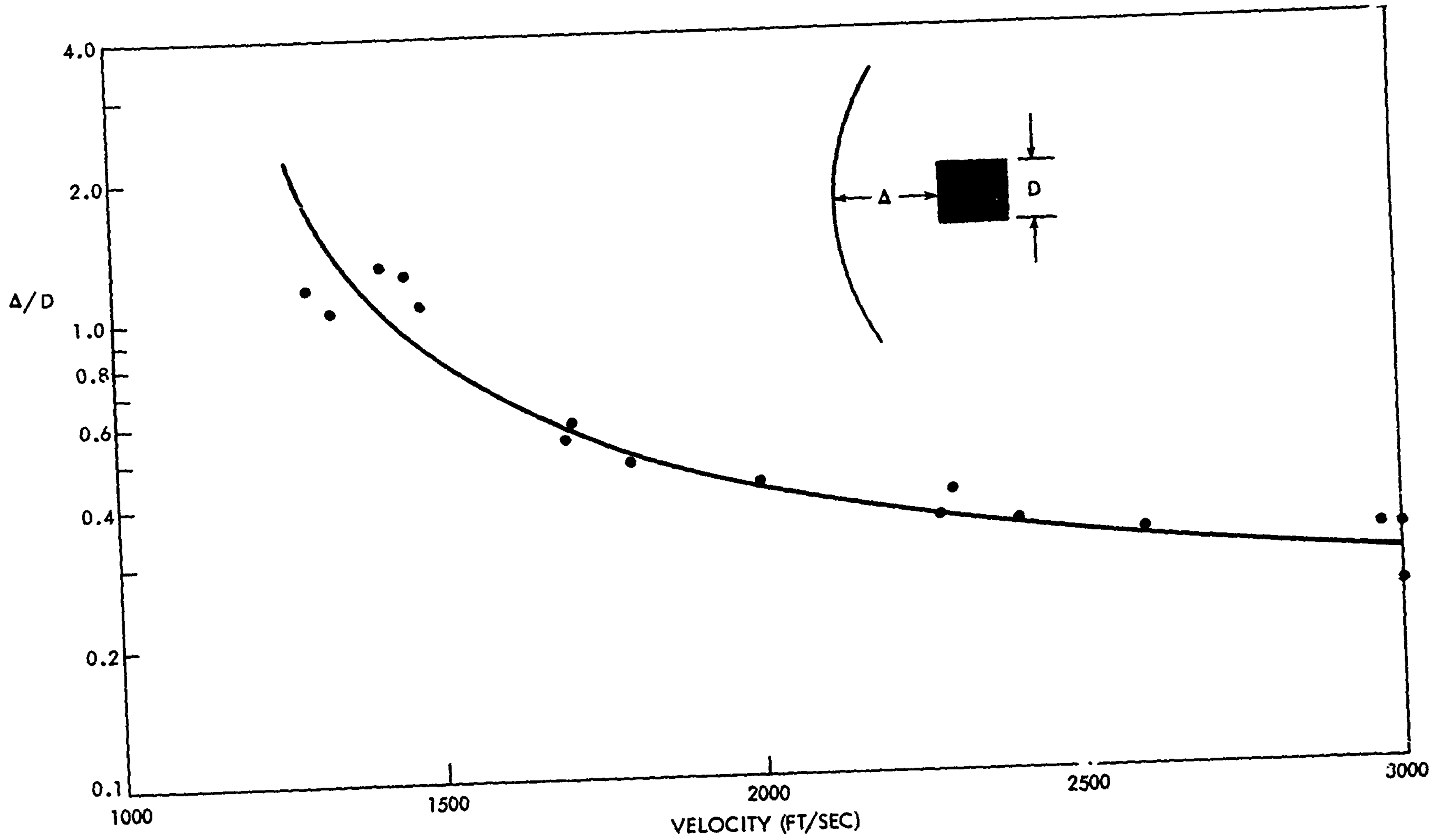


FIG. 21 EXPERIMENTAL VALUES, SHOCK DETACHMENT

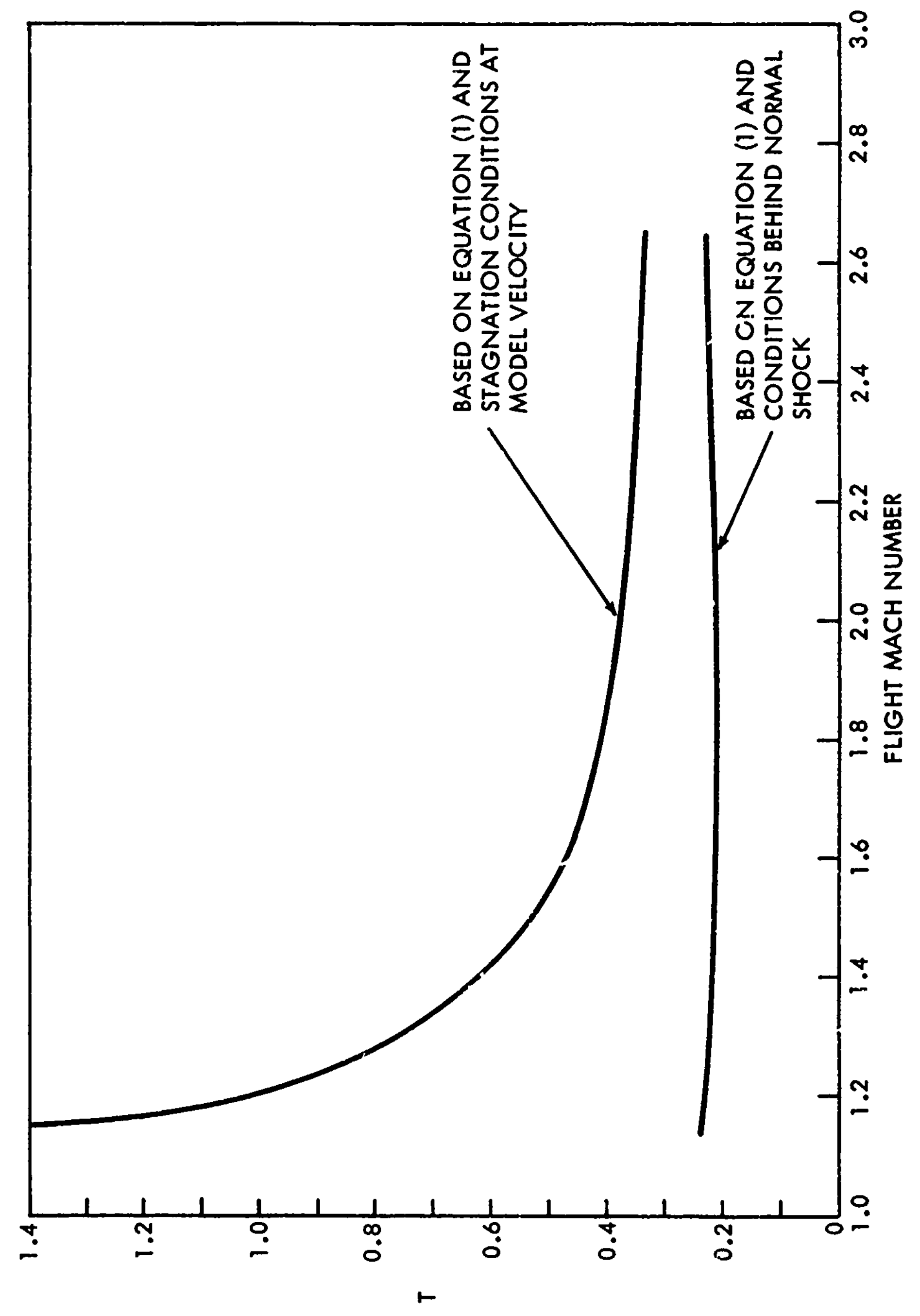


FIG. 22 NON-DIMENSIONLESS TIME FACTORS, T

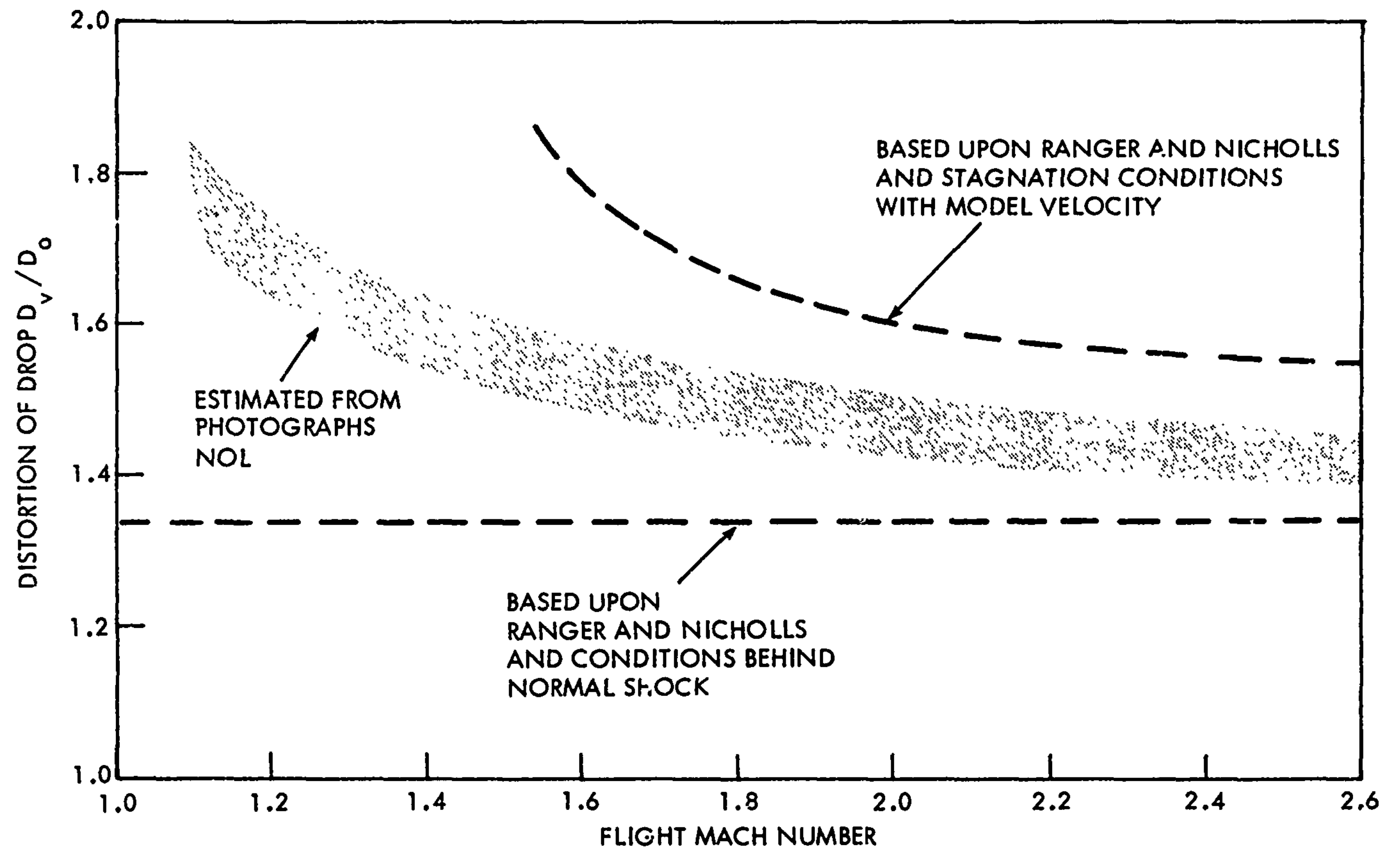


FIG. 23 ESTIMATES OF DROP DISTORTION

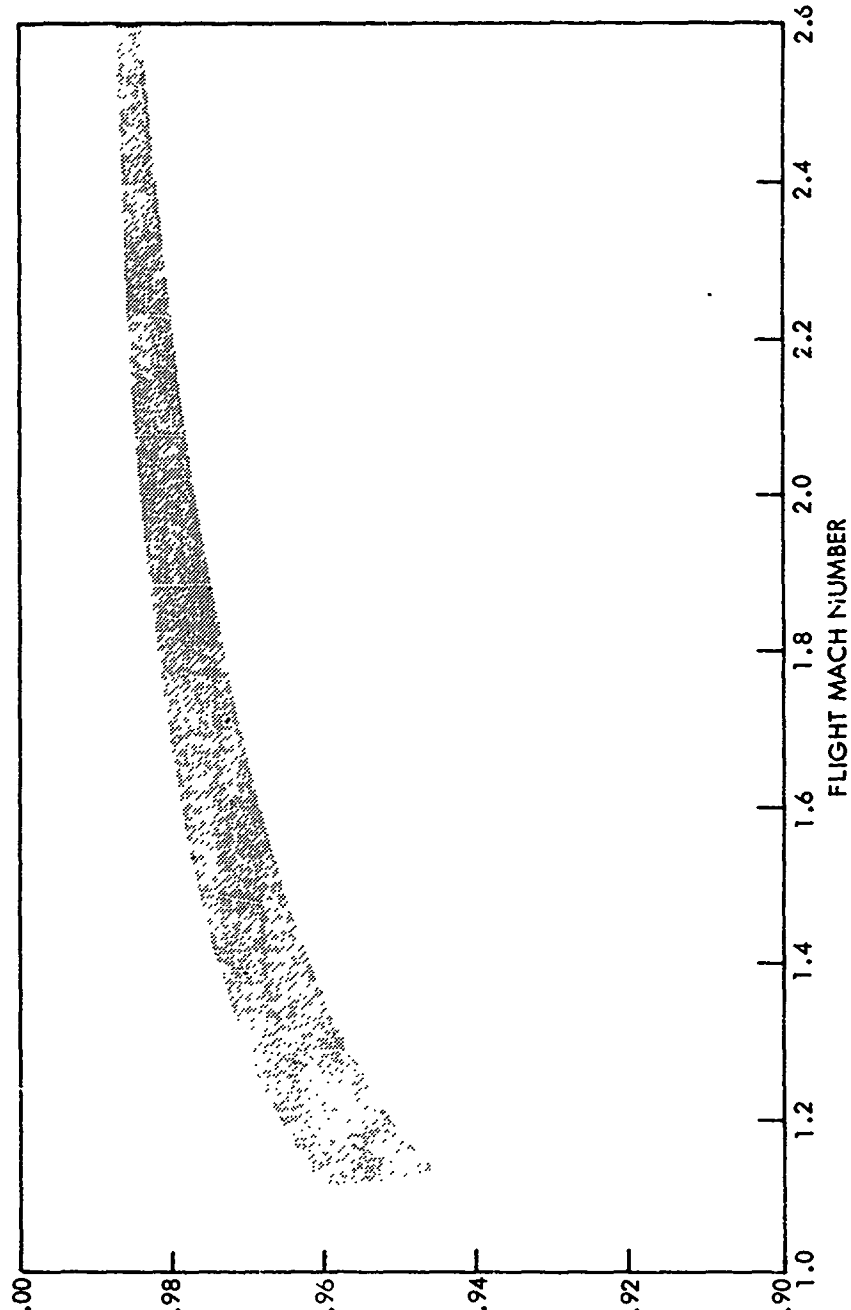


FIG. 24 ESTIMATES OF DROP STRIPPING

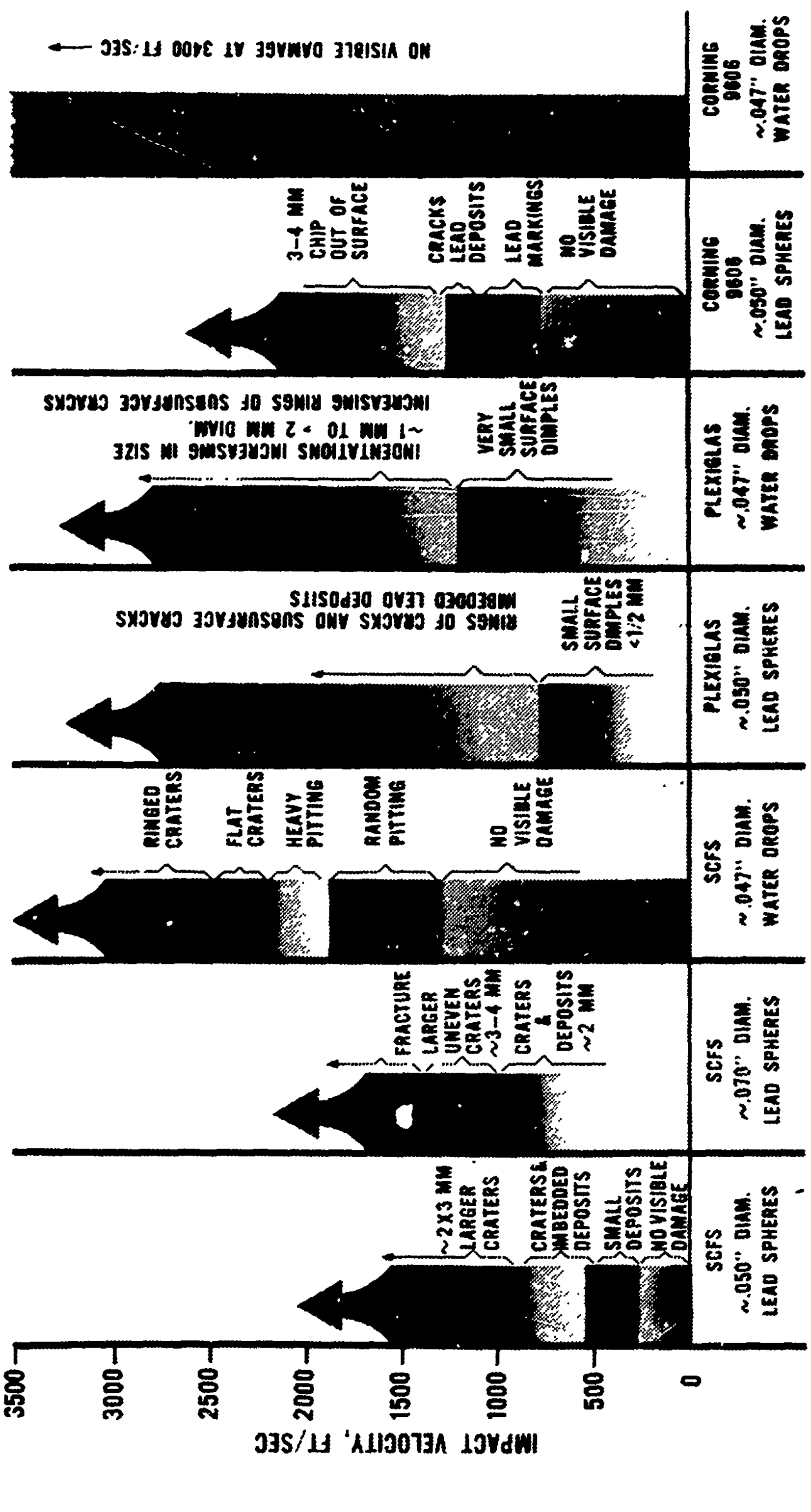


FIG. 25 DISCRETE IMPACT DAMAGE THRESHOLDS

APPENDIX A

BIBLIOGRAPHY AND COMMENTS

(1) "Rain Erosion at Subsonic and Supersonic Speeds," An annotated bibliography compiled by A. A. Beltran, Lockheed Missiles and Space Division, Lockheed Aircraft Company, Sunnyvale, Calif., Special Bibliography SB-62-6, NORD Contract 17017, ASTIA No. 276495, March 1962.

This document lists with brief descriptions 91 documents on rain erosion.

(2) One of the references listed in Beltran's compilation:

Engel, O. G., "Mechanism of Rain Erosion," Part X

This "Review and Evaluation of the State of the Problem" through 1957 lists 100 references many of which do not appear in Beltran's list. Some of these date from Royal Society Proceedings as early as 1877.

Based upon a search of recent literature and knowledge of recent Defense Department activity in areas of ablation and erosion it seems a reasonable estimate that in the approximately ten years since Engel's review two or three hundred additional references must have been generated. There has been no attempt in this program, therefore, to assume responsibility for the thorough search and comprehension of literally hundreds of documents generated over almost a 100-year period.

A partial list follows of some of the documents written since the summaries of (A) and (B) that bear upon the general problem.

(3) Wahl, N. E., "Investigation of the Phenomena of Rain Erosion at Subsonic and Supersonic Speeds," AFML-TR-65-330, October 1965.

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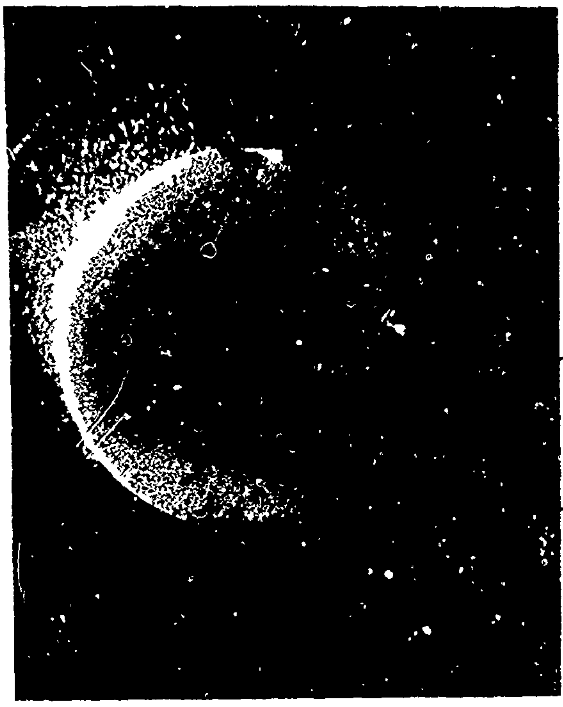
APPENDIX B

REPRESENTATIVE DATA SHEETS FROM PHASE I INVESTIGATIONS

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	88	SPECIMEN DATA	
velocity	1700 F/S	material	SCFS
pressure	1 ATM	group	I
yaw angle	4°	size	½"
sabot dia.	0.8"		
sabot mat'l	POLYE.		



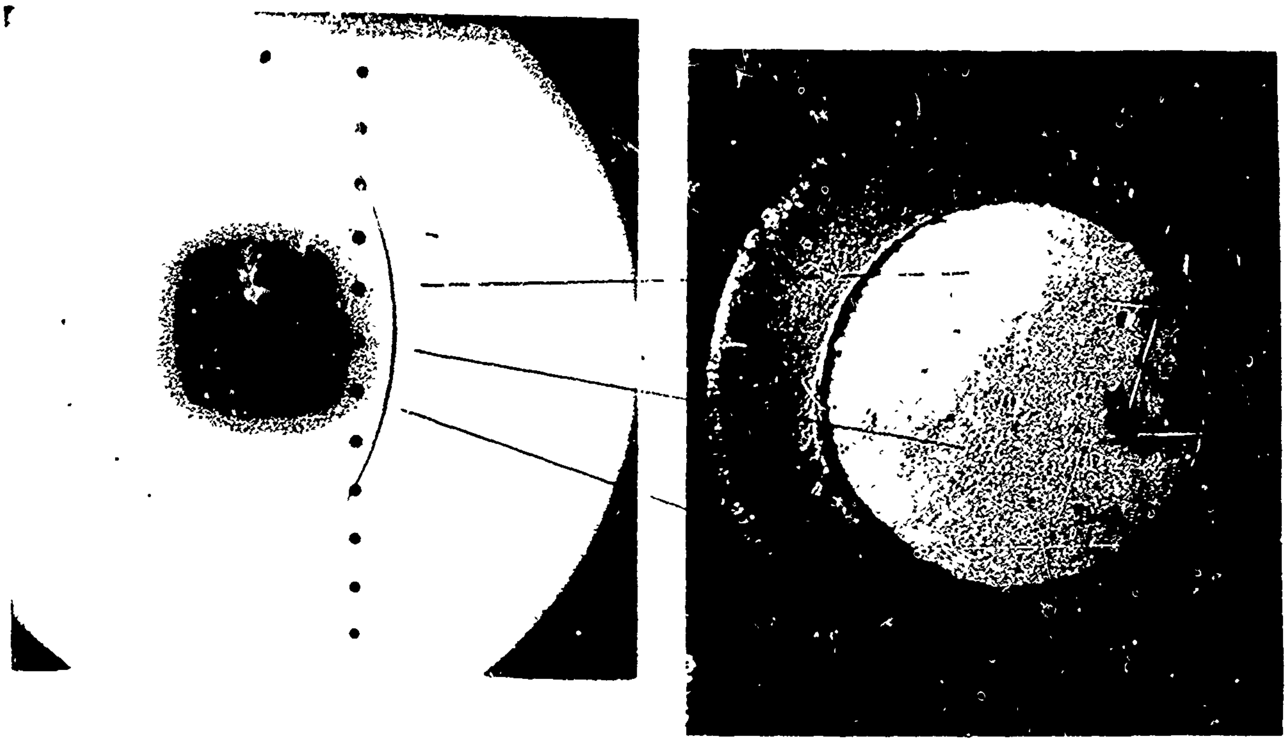
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.2 mm	Evaluation:	
composition	WATER	RANDOM PITTING	
Dv/Do	1.55		
Dh/Do	—		
Ms/Mo	.965		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 81
- velocity 1790 F/S
- pressure 1 ATM
- yaw angle 0°
- sabot dia. 0.8"
- sabot mat'l POLYC.

SPECIMEN DATA
- material [illegible]
- group I
- size 1/2"



NOT REPRODUCIBLE

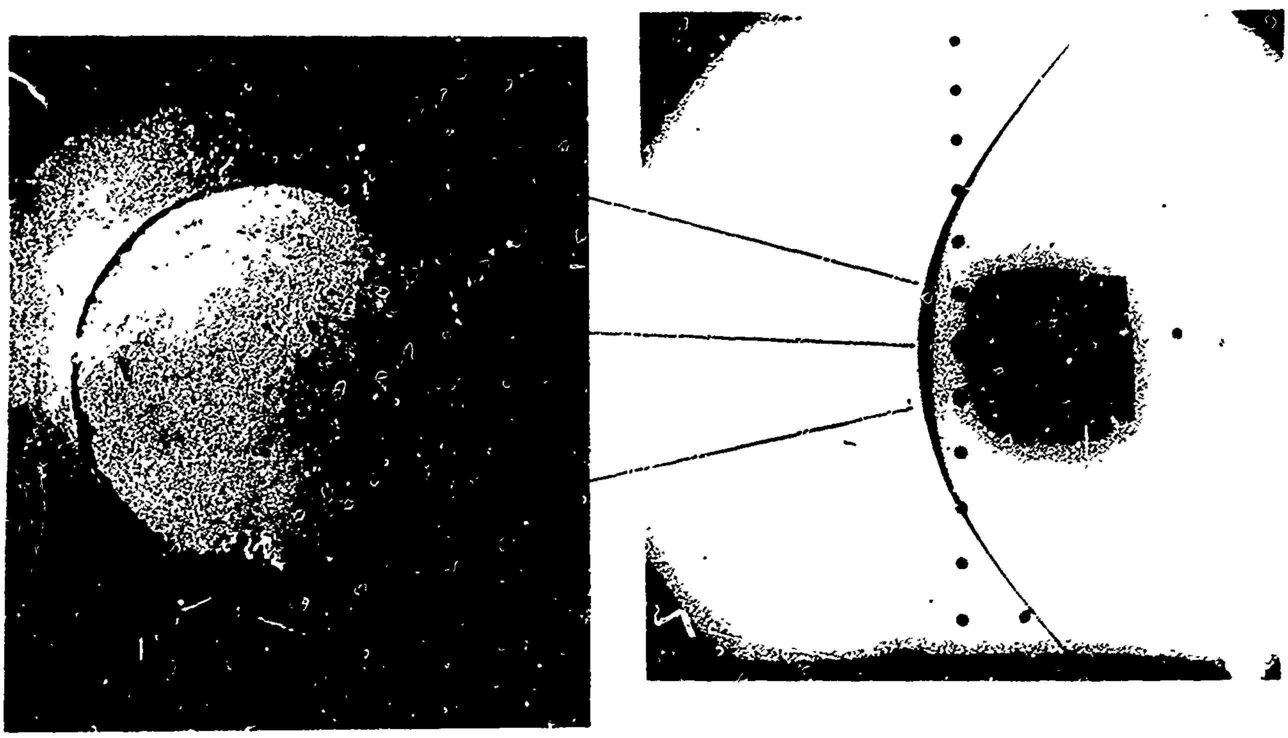
PARTICLE DATA
- diameter 1.2 mm
- composition WATER
- Dv/Do 1.55
- Dh/Do —
- Ms/Mo .965

PRELIMINARY IMPACT DAMAGE
- Evaluation:
- RANDOM PITTING

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	87	SPECIMEN DATA	
velocity	1920 F/S	material	SCFS
pressure	1 ATM	group	I
yaw angle	2°	size	½"
sabot dia.	0.8"		
sabot mat'l	POLYE		



NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.2 mm	Evaluation:	
composition	WATER	MODERATE PITTING	
Dv/Do	1.5		
Dh/Do	—		
Ms/Mo	.98		

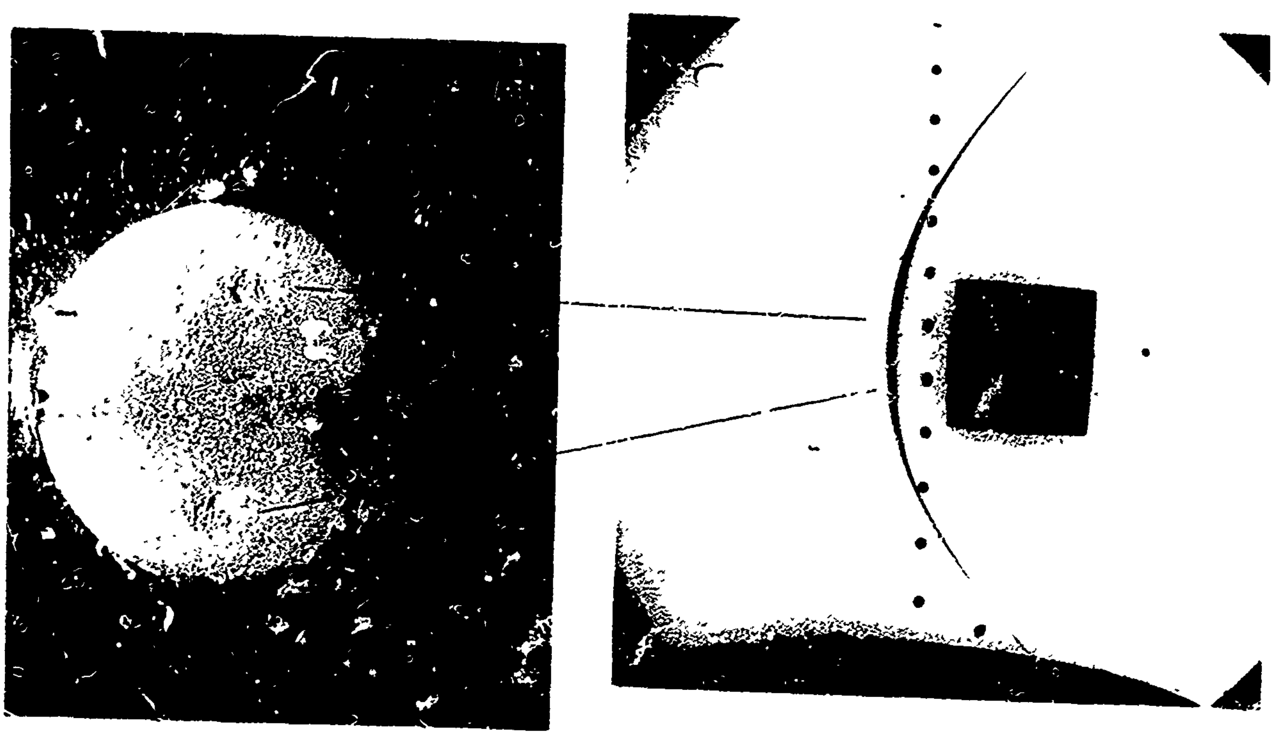
AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	86
velocity	1980 m/s
pressure	1 ATM
yaw angle	2.5°
sabot dia.	0.8"
sabot mat'l	POLYC

SPECIMEN DATA

material	SCFS
group	I
size	1/2"



NOT REPRODUCIBLE

PARTICLE DATA

diameter	1.2 mm
composition	WATER
Dv/Do	1.5
Dh/Do	—
Ms/Mo	.98

PRELIMINARY IMPACT DAMAGE

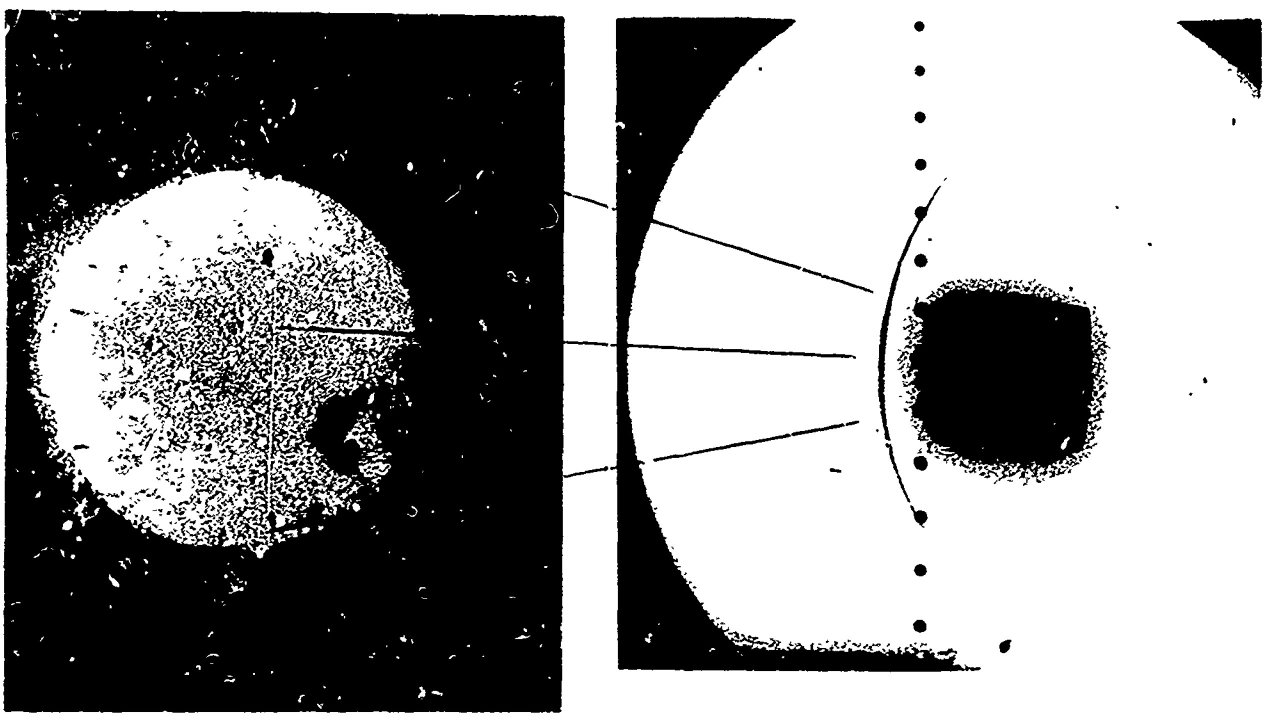
Evaluation:

MODERATE PITTING

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	82	SPECIMEN DATA	
velocity	1990 m/s	material	SCFS
pressure	1 ATM	group	I
yaw angle	5°	size	½"
sabot dia.	0.8"		
sabot mat'l	Poly.		

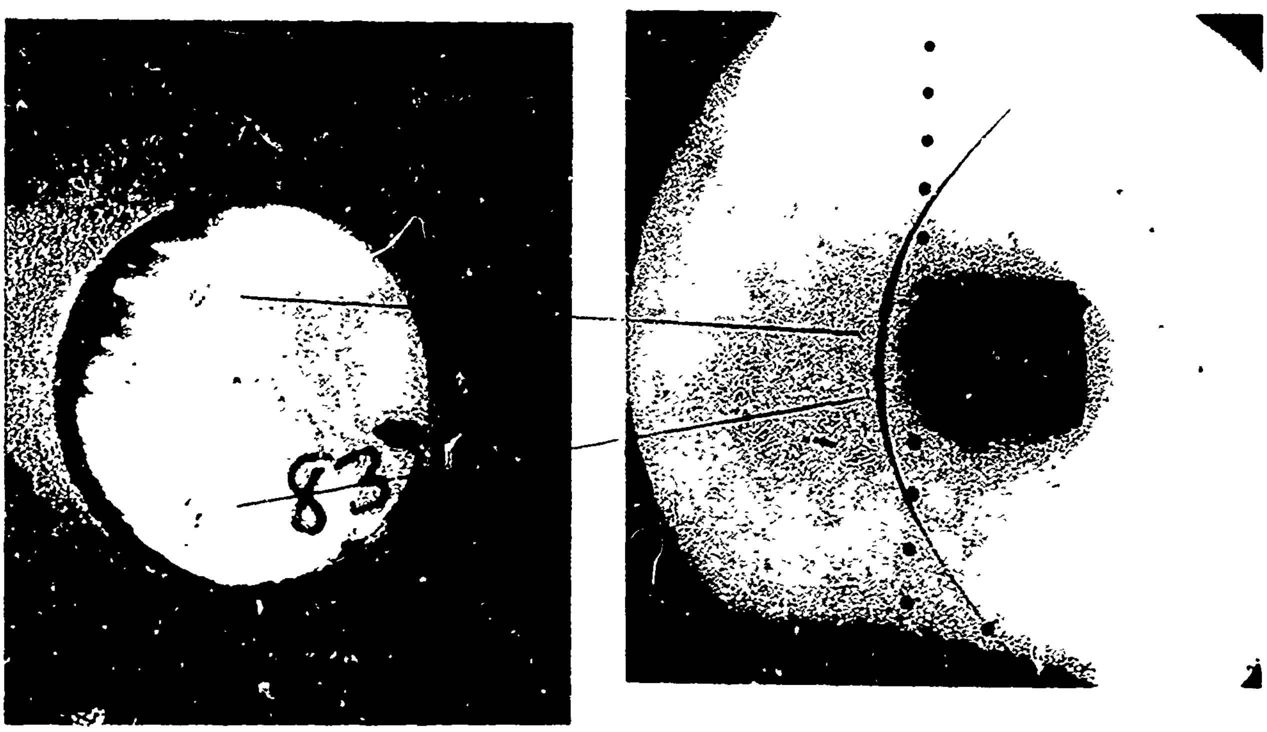


NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.2 mm	Evaluation:	
composition	WATER	MODERATE PITTING	
Dv/Do	1.5		
Dh/Do	—		
Ms/Mo	.98		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	83	SPECIMEN DATA	
velocity	2260 F/s	material	SCFS
pressure	1 ATM	group	I
yaw angle	5°	size	1/2"
sabot dia.	0.8		
sabot mat'l	POLYE.		



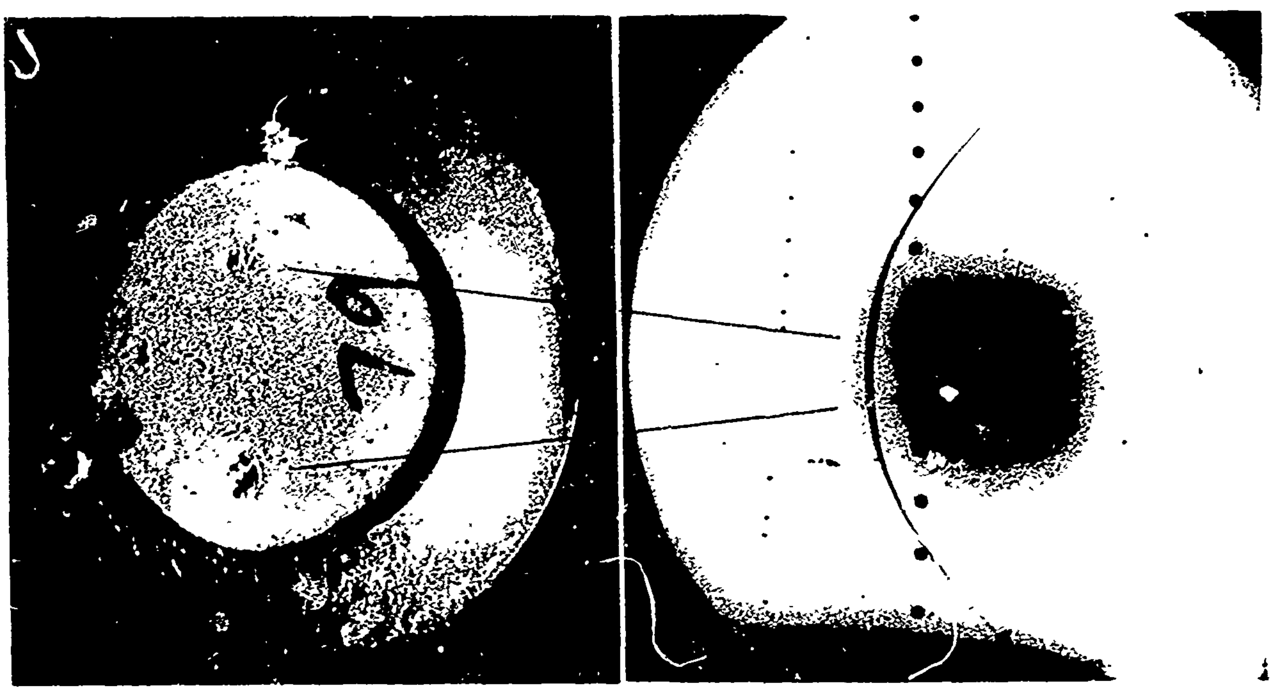
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.2 mm	Evaluation:	
composition	WATER	MODERATE PITTING	
Dv/Do	15		
Dh/Do	—		
Ms/Mo	.98		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	79	SPECIMEN DATA	
velocity	2120 F/S	material	SCFS
pressure	1 ATM	group	I
yaw angle	2°	size	½"
sabot dia.	0.8		
sabot mat'l	POLYC		



NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.2 mm	Evaluation:
composition	WATER	MODERATE TO
Dv/Do	1.47	HEAVY PITTING
Dh/Do	—	
Ms/Mc	.973	

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 85

velocity 2235 F/S

pressure 1 ATM

yaw angle 4.5°

sabot dia. 0.8"

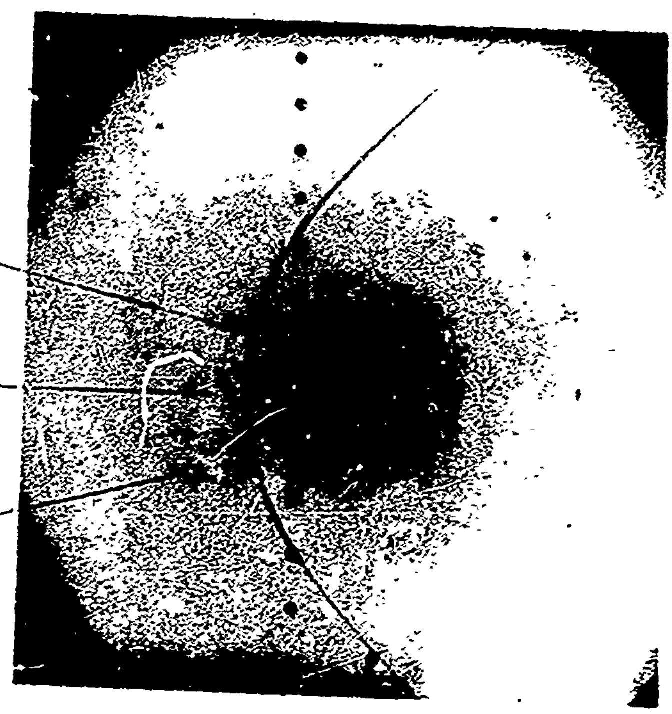
sabot mat'l POLYE.

SPECIMEN DATA

material SCFS

group I

size 1/2



NOT REPRODUCIBLE

PARTICLE DATA

diameter 1.2 mm

composition WATER

Dv/Do 1.43

Dh/Do ——

Ms/Mo .975

PRELIMINARY IMPACT DAMAGE

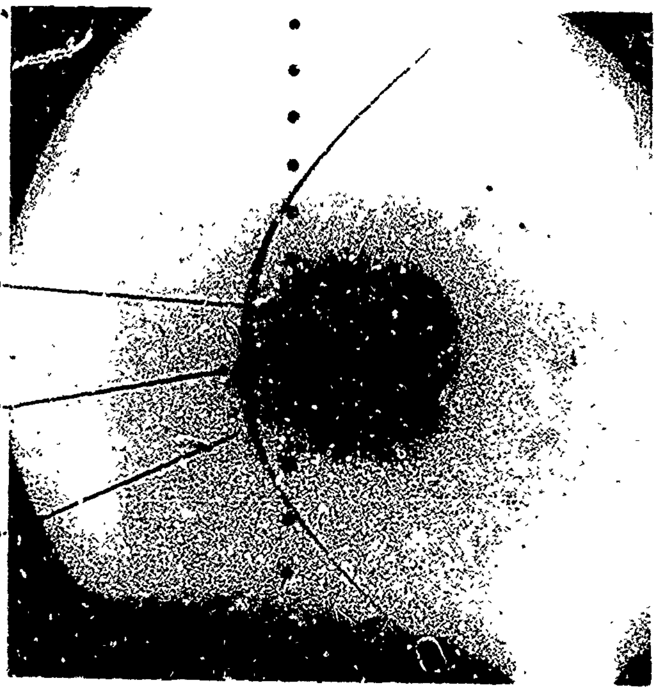
Evaluation:

HEAVY PITTING

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	84	SPECIMEN DATA	
velocity	2280 F/s	material	SCFS
pressure	1 ATM	group	I
yaw angle	2.5°	size	1/2"
sabot dia.	0.8"		
sabot mat'l	POLYE.		



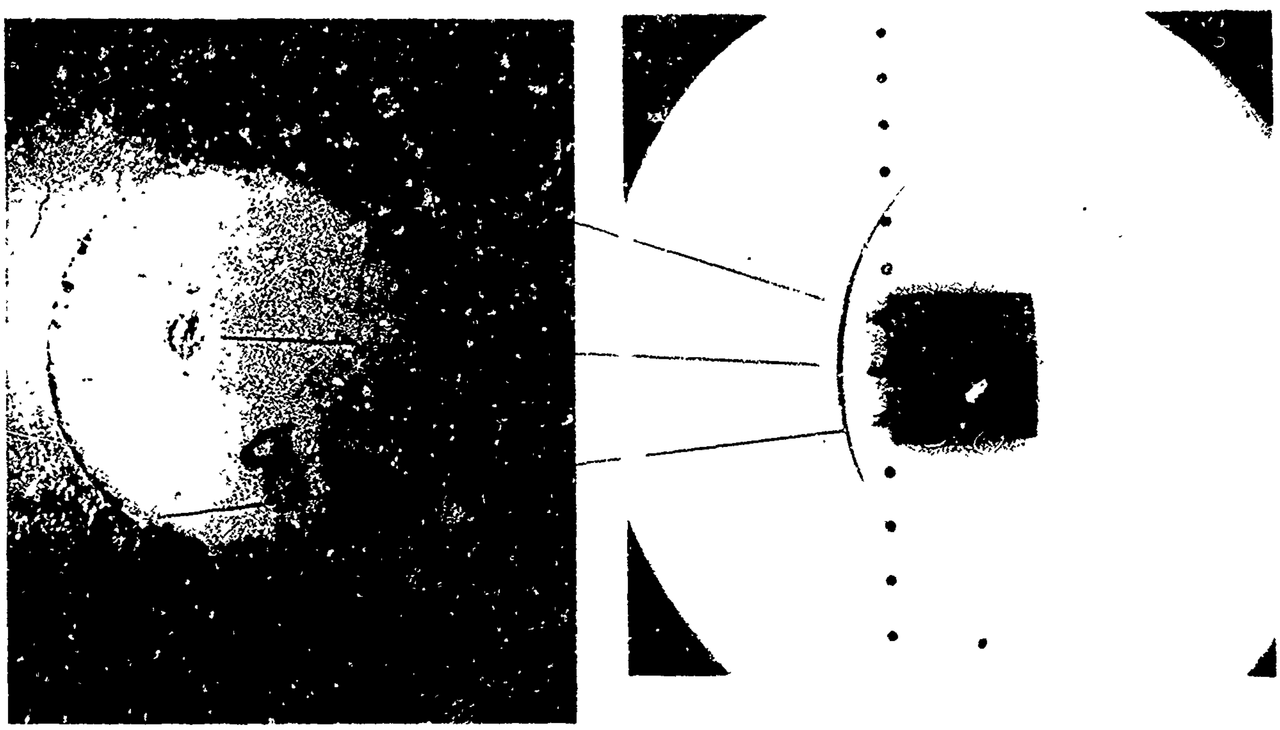
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.2 mm	Evaluation:	
composition	WATER	HEAVY PITTING	
Dv/Do	1.43		
Dh/Do	—		
Ms/Mo	.975		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	8c	SPECIMEN DATA	
velocity	2290 f/s	material	SCFS
pressure	1 ATM	group	I
yaw angle	0°	size	1/2"
sabot dia.	0.5"		
sabot mat'l	POLYE		



NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.2 mm	Evaluation:
composition	WATER	HEAVY PITTING,
Dv/Do	1.43	CRATERING
Dh/Do	—	
Ms/Mo	.975	

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 78

velocity 2620 F/S

pressure 1 MM

yaw angle 0°

sabot dia. 0.8"

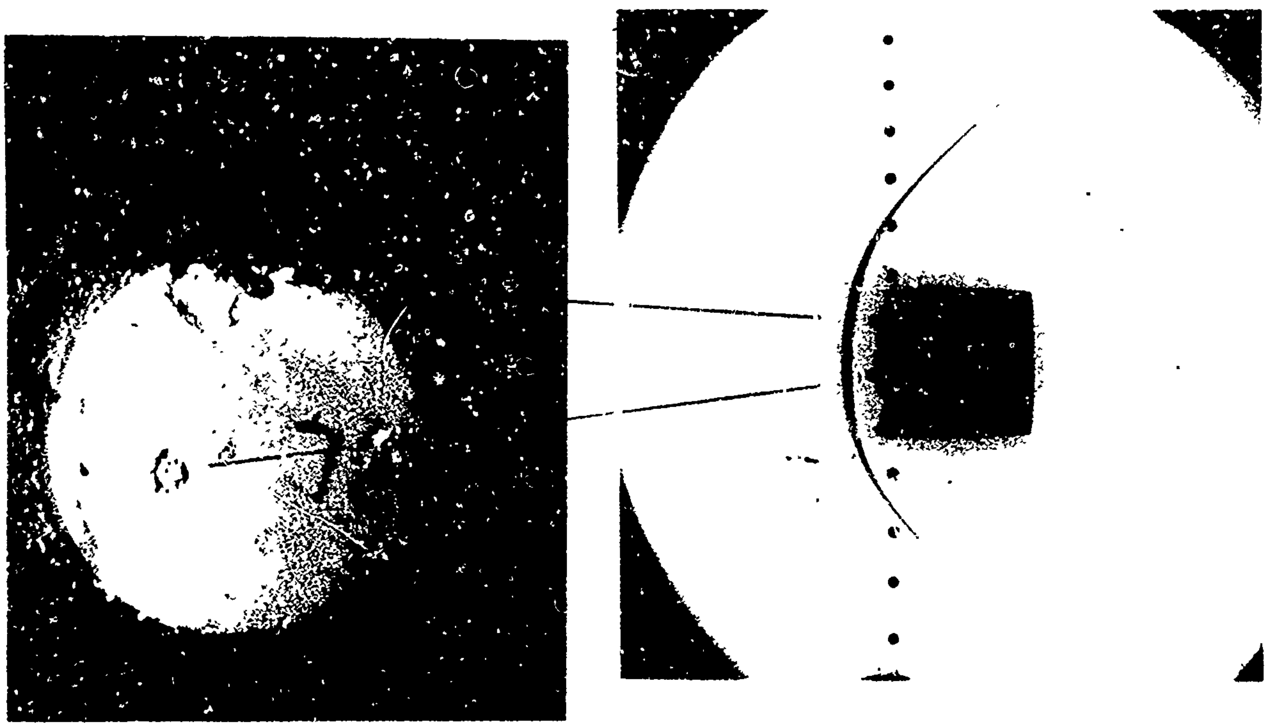
sabot mat'l POLYE

SPECIMEN DATA

material SCFS

group I

size 1/2"



NOT REPRODUCIBLE

PARTICLE DATA

diameter 1.2 mm

composition WATER

Dv/Do 1.41

Dh/Do —

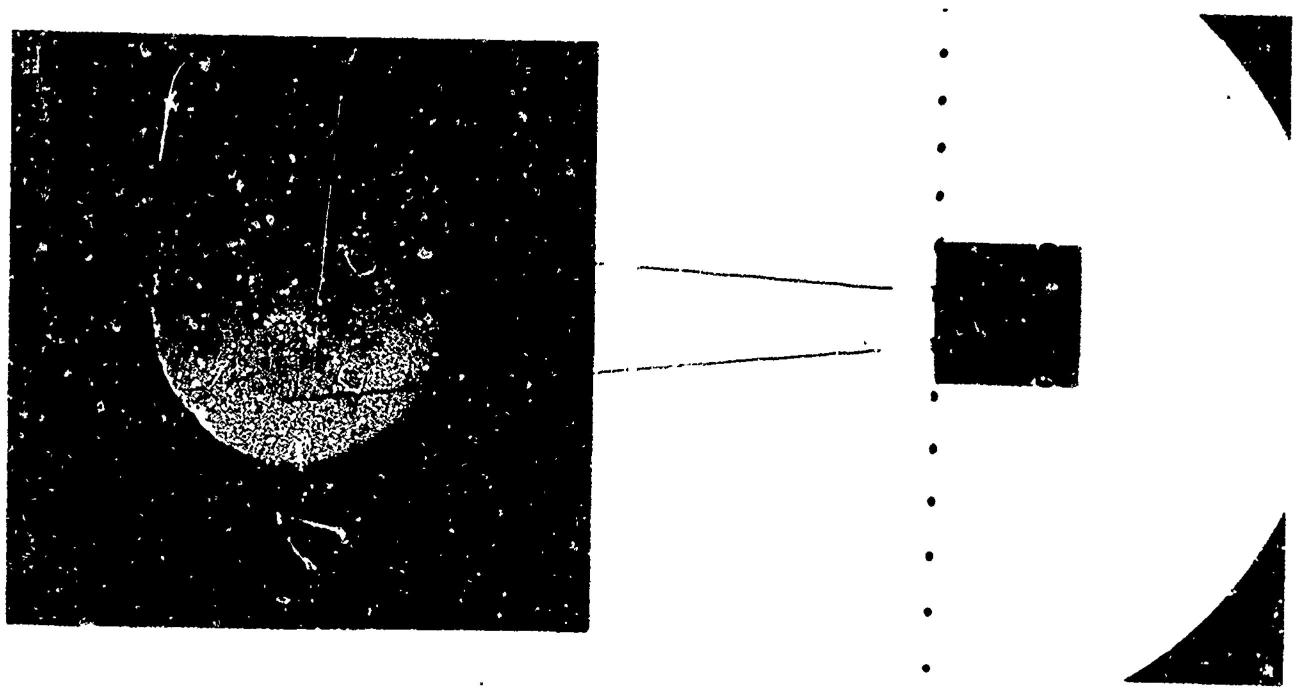
Ms/Mo .98

PRELIMINARY IMPACT DAMAGE

Evaluation: RING CRATERING

NOLTR 71-113
AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	159	SPECIMEN DATA	
velocity	1260 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	0°	size	½"
sabot dia.	.801"		
sabot mat'l	POLYE		



NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	~1.2 MM	Evaluation:	LOWER LIMIT OF RANDOM PITTING
composition	WATER		
Dv/Do	1.7 TO 2		
Dh/Do	—		
Ms/Mo	0.94 TO 0.96		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 161

velocity 1285 F/S

pressure 1 ATM

yaw angle 0°

sabot dia. .801"

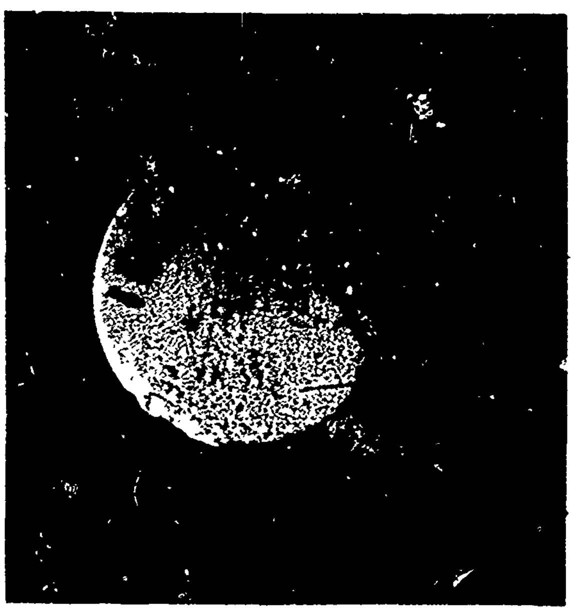
sabot mat'l POLYE

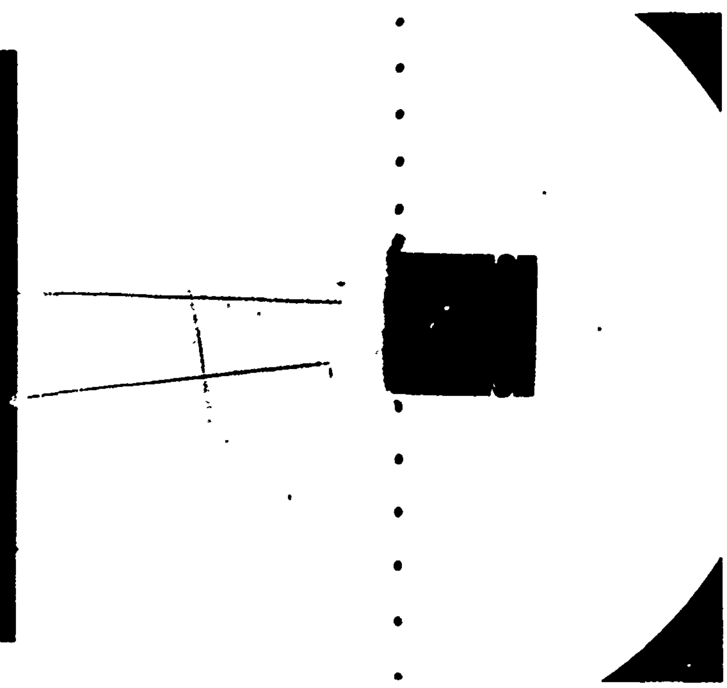
SPECIMEN DATA

material SCFS

group VI

size ½"





NOT REPRODUCIBLE

PARTICLE DATA

diameter ~1.2 mm

composition WATER

Dv/Do 1.7 TO 1.9

Dh/Do —

Ms/Mo 0.94 TO 0.96

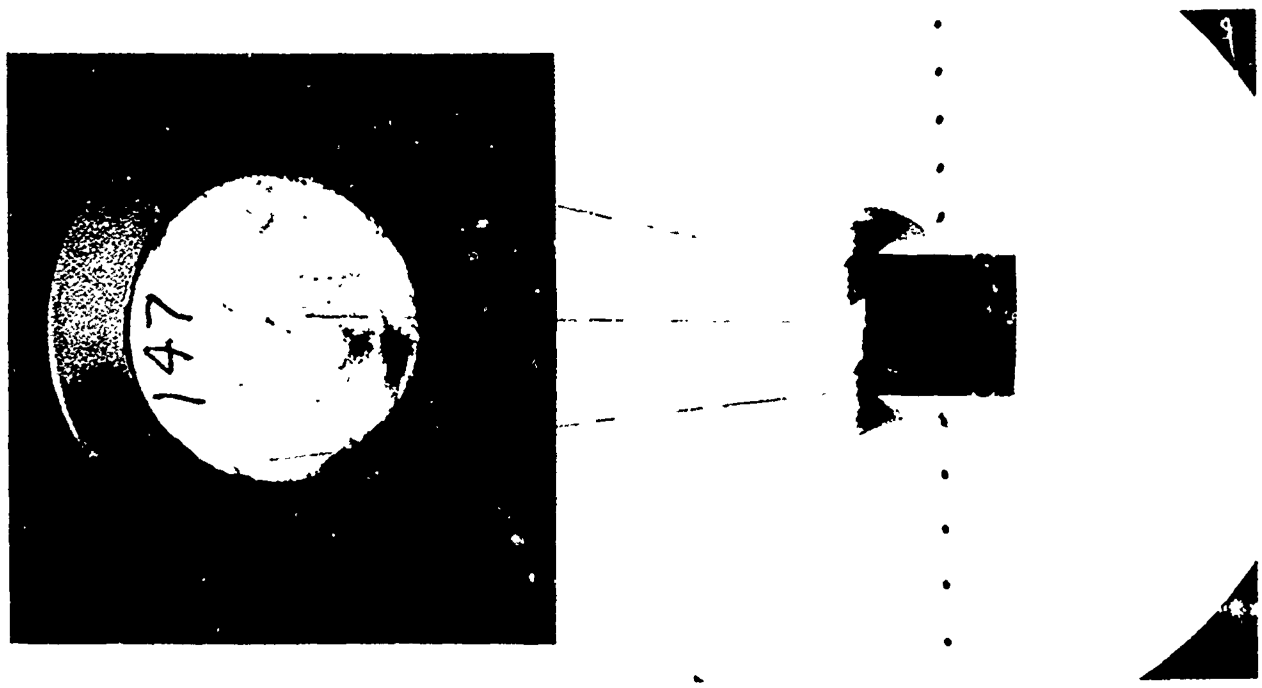
PRELIMINARY IMPACT DAMAGE

Evaluation: LOWER LIMIT OF RANDOM PITTING.

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	147	SPECIMEN DATA	
velocity	1290 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	2°	size	1/2"
sabot dia.	.801"		
sabot mat'l	POLYE		



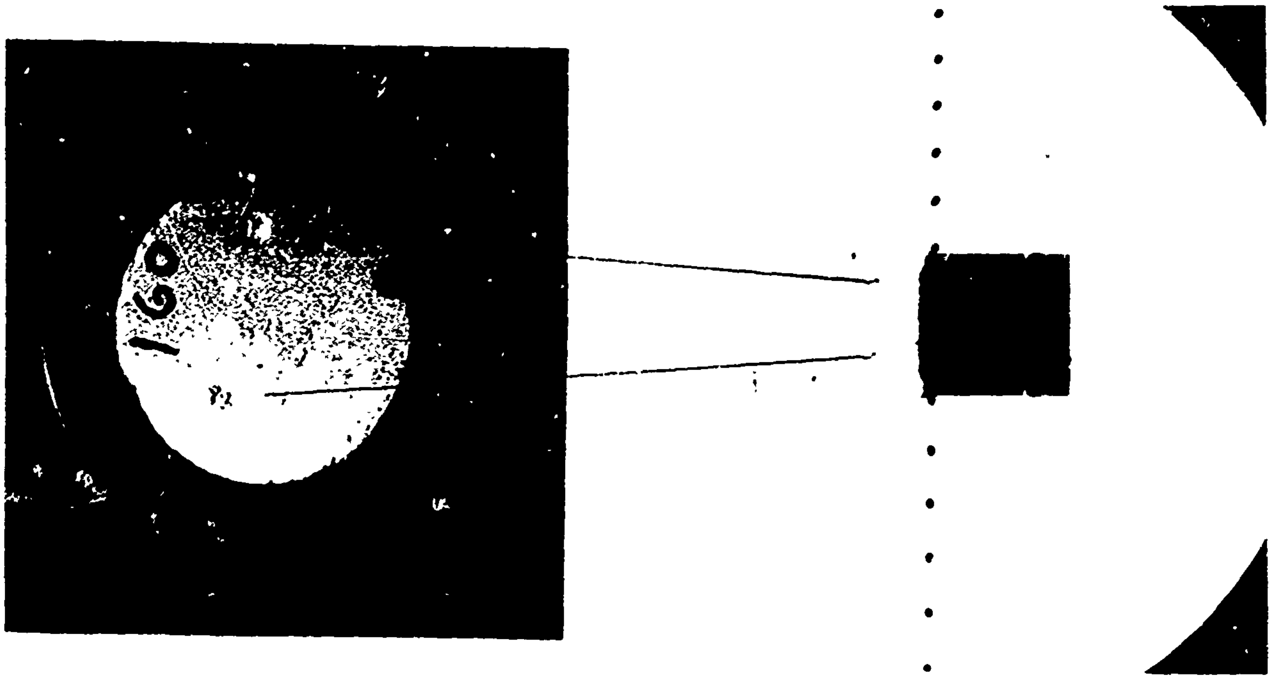
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	~1.2 mm	Evaluation:	LOWER LIMIT OF RANDOM PITTING
composition	WATER		
Dv/Do	1.7 TO 1.9		
Dh/Do	—		
Ms/Mo	.94 TO .96		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 160
velocity 1320 F/S
pressure 1 ATM
yaw angle 0°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material SCFS
group VI
size ½"



NOT REPRODUCIBLE

PARTICLE DATA
diameter ~1.2 mm
composition WATER
Dv/Do 1.65 TO 1.75
Dh/Do —
Ms/Mo 0.95 TO 0.965

PRELIMINARY IMPACT DAMAGE
Evaluation: ~1.3 MM DIA CRATERING EARLIER THAN OTHER SPECIMENS

AEROPHYSICS RANGE

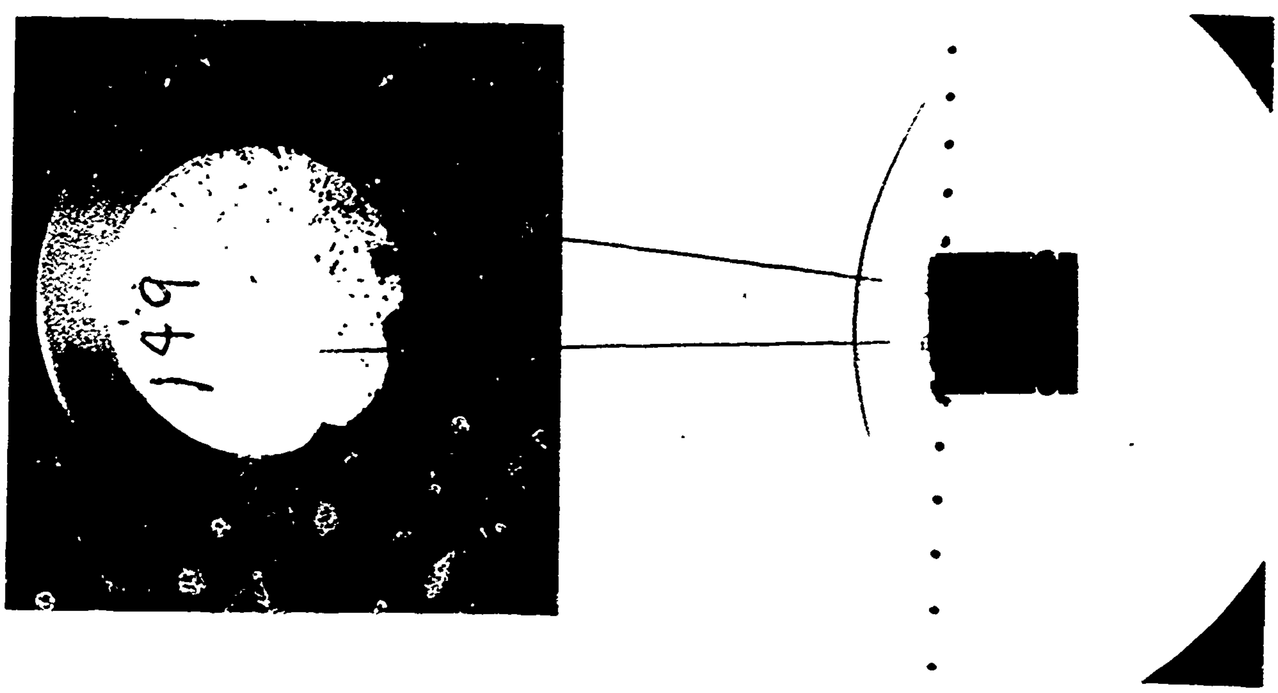
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 149

- velocity: 1665 F/S
- pressure: 1 ATM
- yaw angle: 1°
- sabot dia.: .801"
- sabot mat'l: POLYE

SPECIMEN DATA

- material: SCFS
- group: VI
- size: ½"



NOT REPRODUCIBLE

PARTICLE DATA

- diameter: ~1.2 mm
- composition: WATER
- Dv/Dc: 1.55
- Dh/Dc: —
- Ms/Mo: .965

PRELIMINARY IMPACT DAMAGE

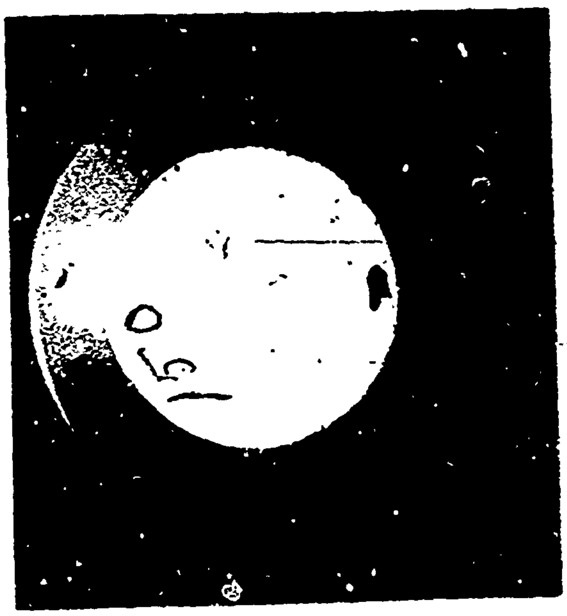
Evaluation:

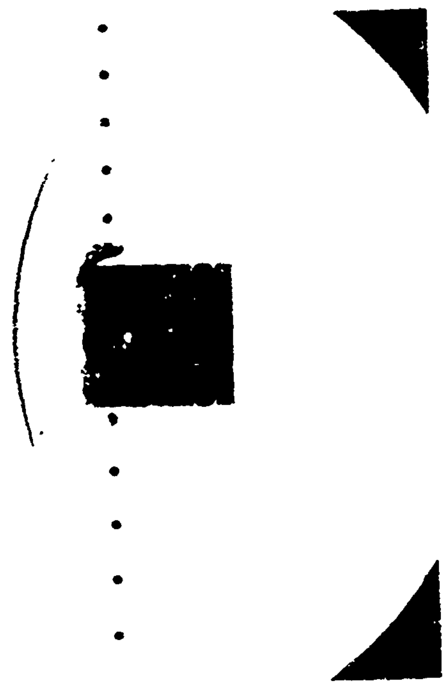
LIGHT PITTING

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	150	SPECIMEN DATA	
velocity	1695 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	0°	size	1/2
sabot dia.	.801		
sabot mat'l	POLYE		





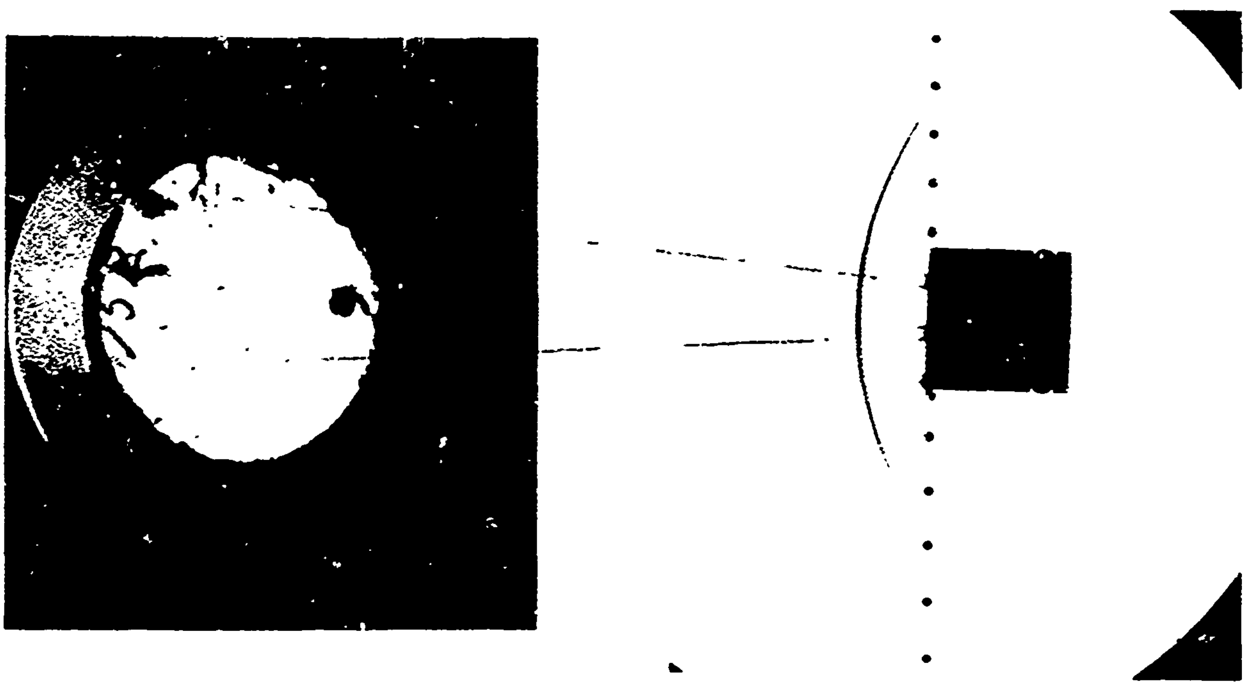
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	~1.2 mm	Evaluation:	
composition	WATER	RANDOM PITTING	
Dv/ Do	1.55		
Dh/ Do	—		
Ms/ Mo	.965		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 152
velocity 1850 F/S
pressure 1 ATM
yaw angle 0°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material SCFS
group VI
size ½"



NOT REPRODUCIBLE

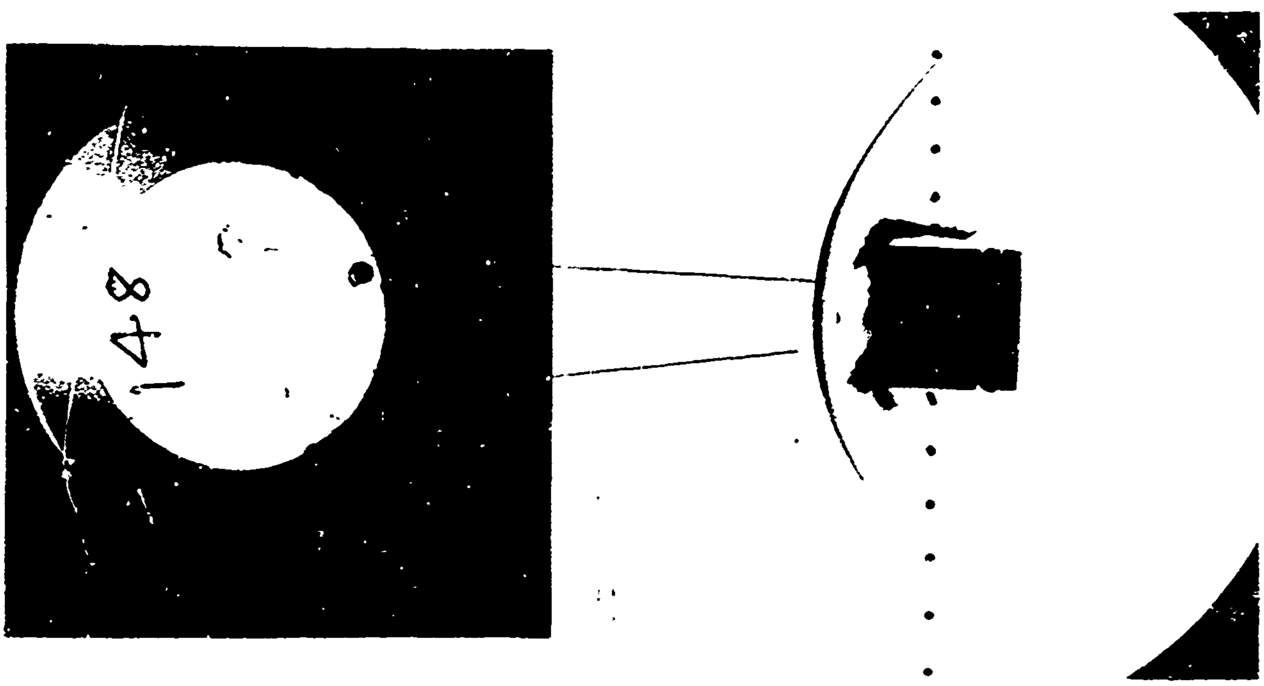
PARTICLE DATA
diameter 1.23 mm
composition WATER
Dv/Do 1.52
Dh/Do —
Ms/Mo .97

PRELIMINARY IMPACT DAMAGE
Evaluation: RANDOM PITTING

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	148	SPECIMEN DATA	
velocity	2015 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	4°	size	1/2"
sabot dia.	.801"		
sabot mat'l	POLYE		



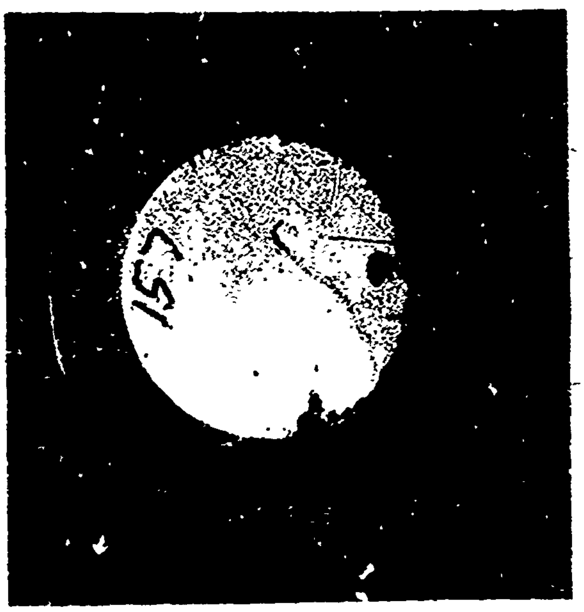
NOT REPRODUCIBLE

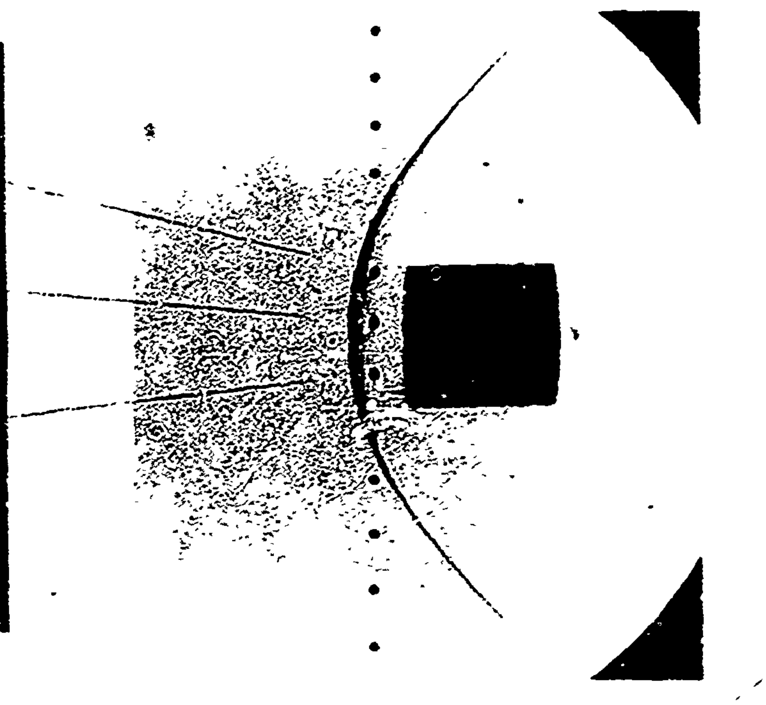
PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	~1.2 mm	Evaluation:	
composition	WATER	CRATERING	
Dv/Do	1.48		
Dh/Do	—		
Ms/Mo	.972		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	157	SPECIMEN DATA	
velocity	2100 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	1°	size	½"
sabot dia.	.801"		
sabot mat'l	POLYS		





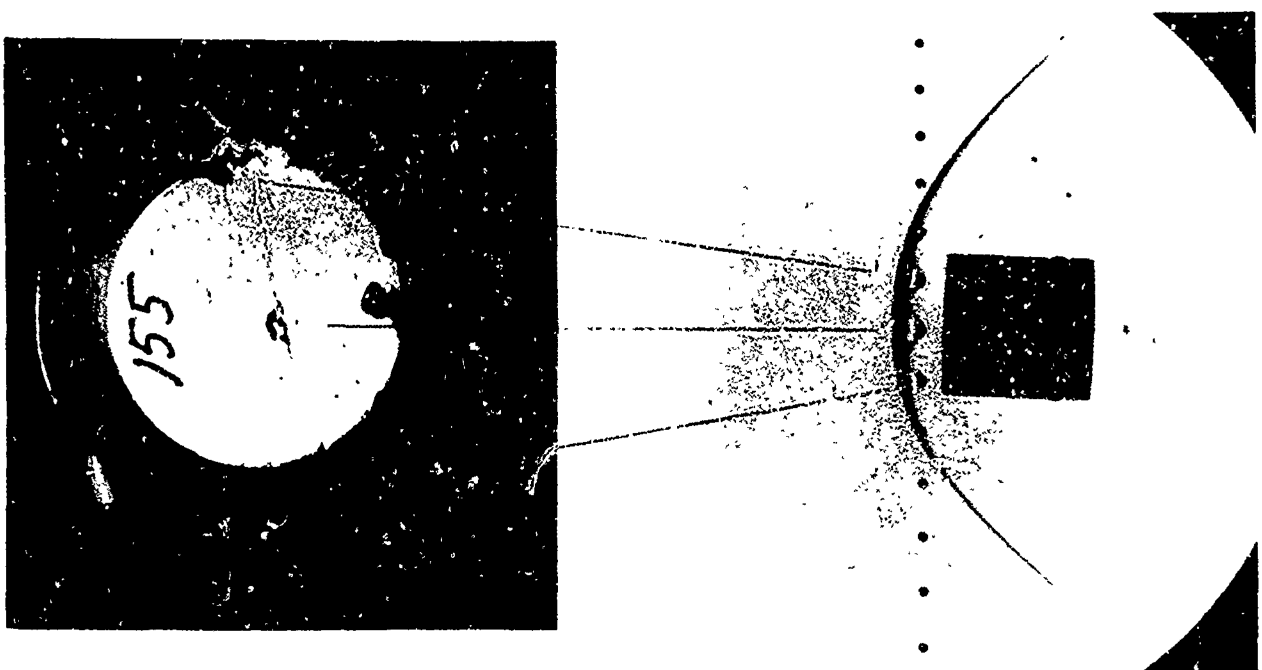
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.26 mm	Evaluation:
composition	WATER	CRATERING
Dv/Do	1.47	
Dh/Do	—	
Ms/Mo	.973	

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	155	SPECIMEN DATA	
velocity	2340 F/s	material	SCFS
pressure	1 ATM	group	VI
yaw angle	4°	size	1/2"
sabot dia.	.801"		
sabot mat'l	POLYE.		



NOT REPRODUCIBLE

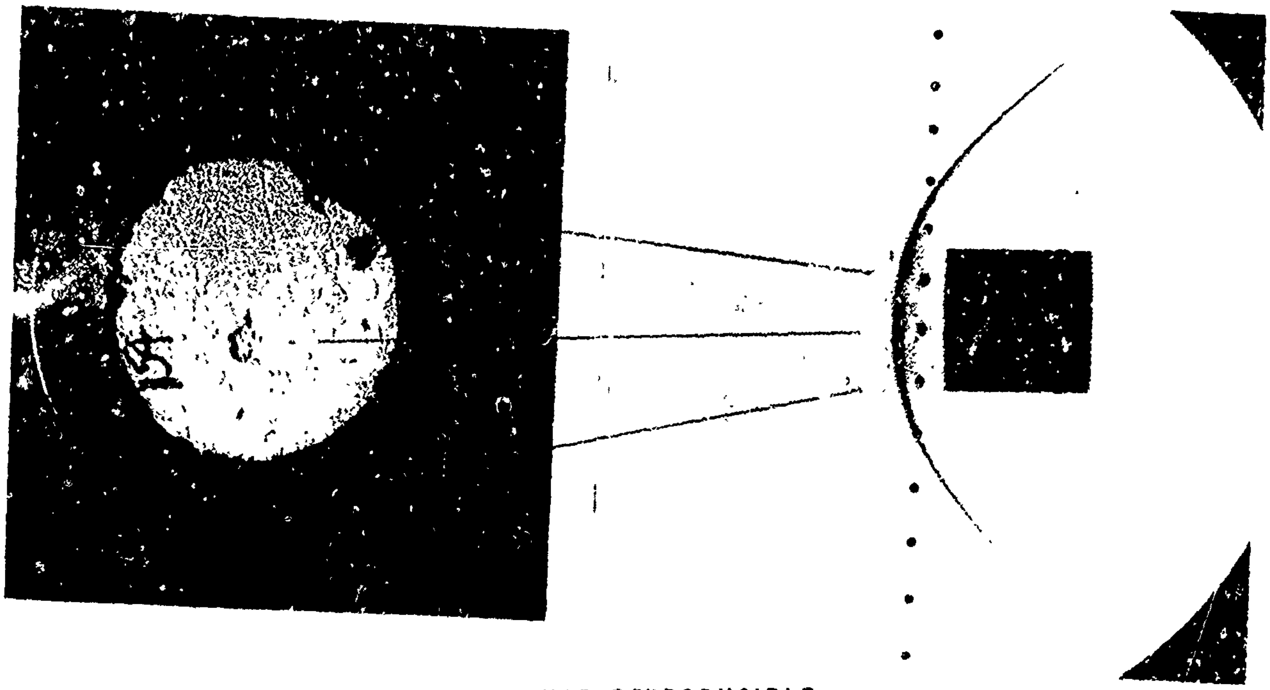
PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.18 mm	Evaluation: UPPER	
composition	WATER	LIMIT OF FLAT	
Dv/Do	1.5	CRATERS. ~1.5 mm DIA.	
Dh/Do	---	SMALL PITS + SURFACE	
Ms/Mo	0.98	IMPERFECTIONS ON MAT'L	
		AS RECEIVED	

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 154
velocity 2360 F/S
pressure 1 ATM
yaw angle 3°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material SCFS
group VI
size 1/2"



NOT REPRODUCIBLE

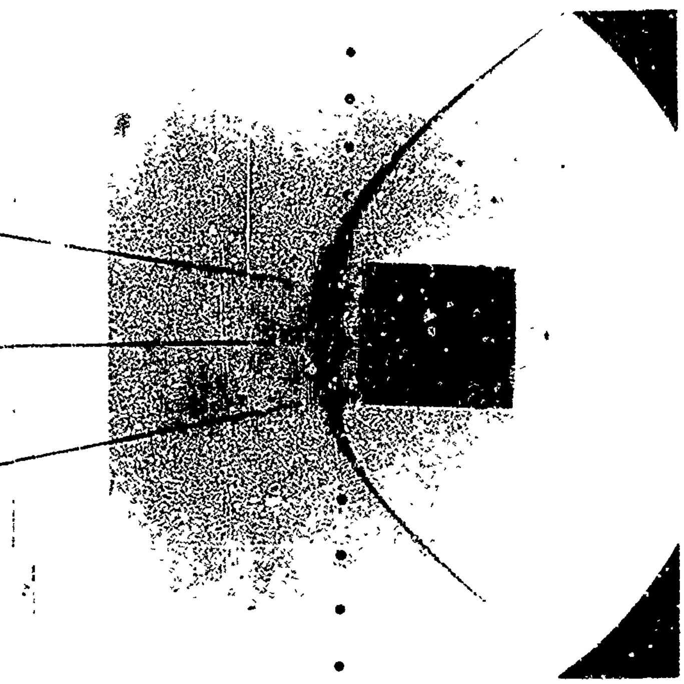
PARTICLE DATA
diameter 1.23 mm
composition WATER
Dv/Do 1.5
Dh/Do —
Ms/Mo .98

PRELIMINARY IMPACT DAMAGE
Evaluation: UPPER LIMIT OF FLAT CRATERS

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 158
velocity 2470 F/S
pressure 1 ATM
yaw angle 1°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material SCFS
group VI
size ½"



NOT REPRODUCIBLE

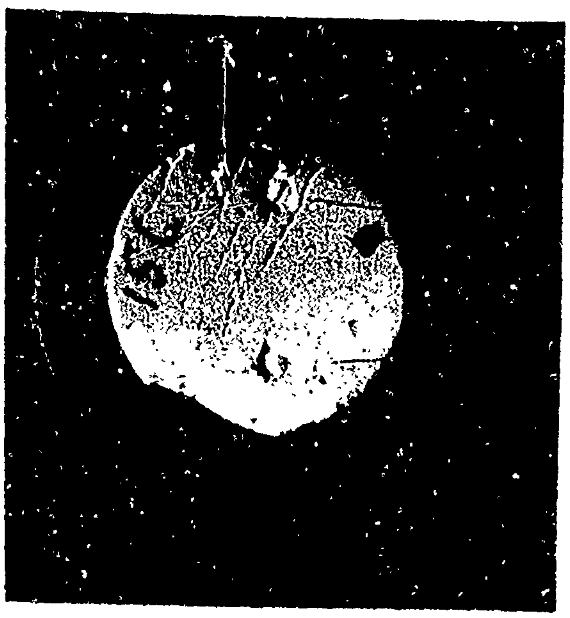
PARTICLE DATA
diameter 1.23 mm
composition WATER
Dv/Do ~~7.5~~ 1.41
Dh/Ds —
Ms/Mo 0.98

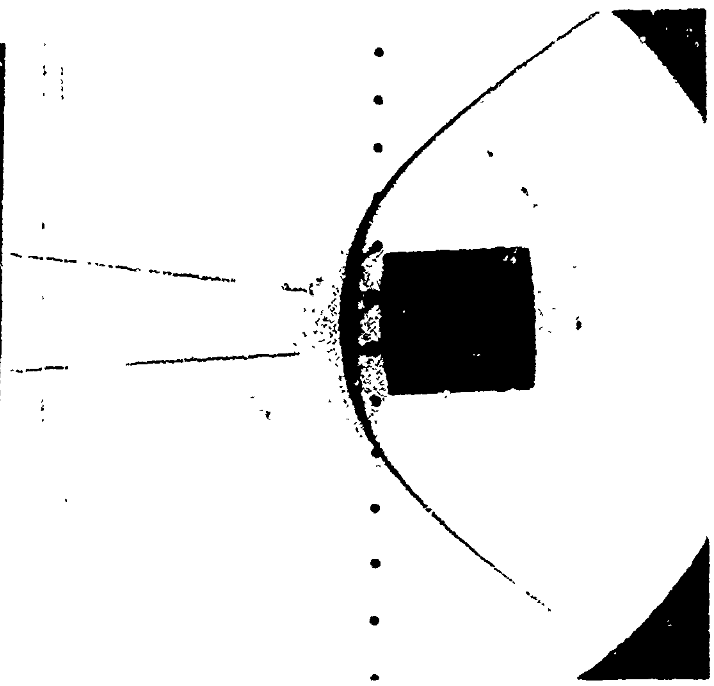
PRELIMINARY IMPACT DAMAGE
Evaluation: ~1.5 mm DIA
UPPER LIMIT OF FLAT
FLOOR CRATER

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	156	SPECIMEN DATA	
velocity	2910 F/S	material	SCFS
pressure	1 ATM	group	VI
yaw angle	3°	size	1/2"
sabot dia.	.801"		
sabot mat'l	POLYE		

NOT REPRODUCIBLE



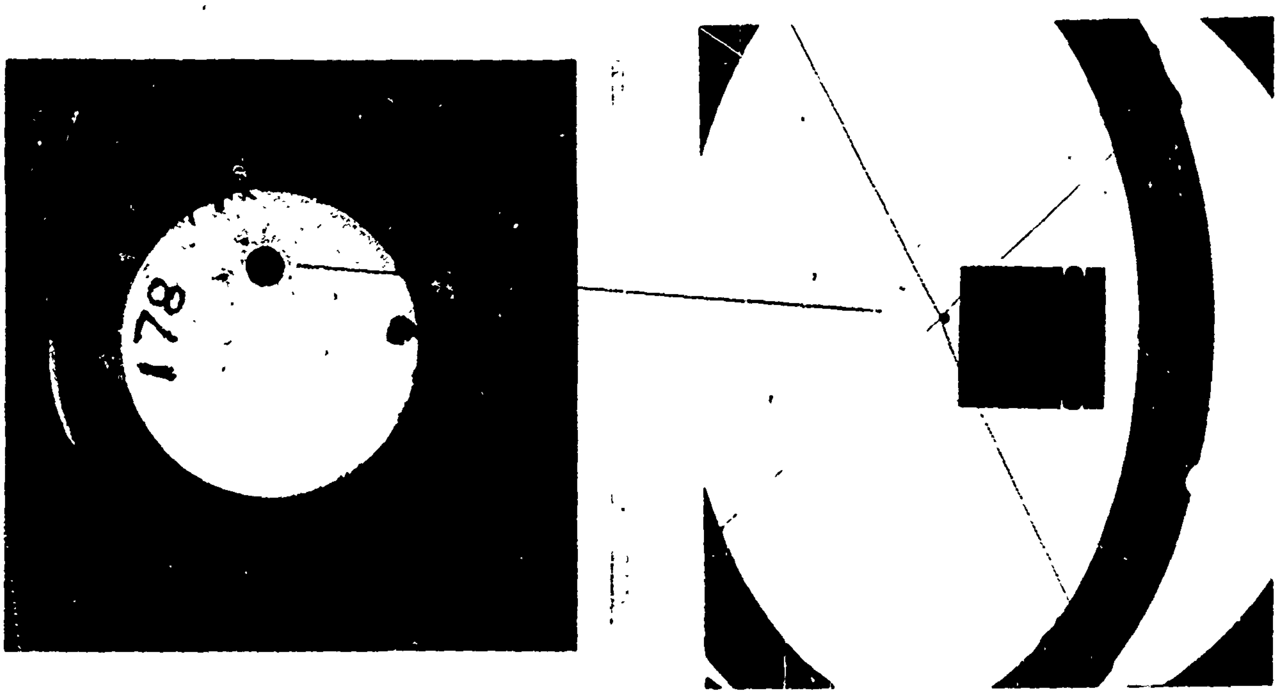


PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.23 mm	Evaluation: ~1.5 mm DIA.	
composition	WATER	HEAVY DAMAGE	
Dv/ Do	1.4	RINGED CRATERS	
Dh/ Do	—		
Ms/ Mo	0.935		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	178	SPECIMEN DATA	
velocity	475 F/s	material	SCFS
pressure	1 ATM	group	VI
yaw angle	1°	size	½"
sabot dia.	.801"		
sabot mat'l	POLYC		



NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	.052"	Evaluation:	
composition	LEAD	NO VISIBLE DAMAGE	
Dv/Do		SMALL DEPOSITS OF	
Dh/Do		LEAD	
Ms/Mo			

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 176

velocity 745 f/s

pressure 1 ATM

yaw angle 1°

sabot dia. .801"

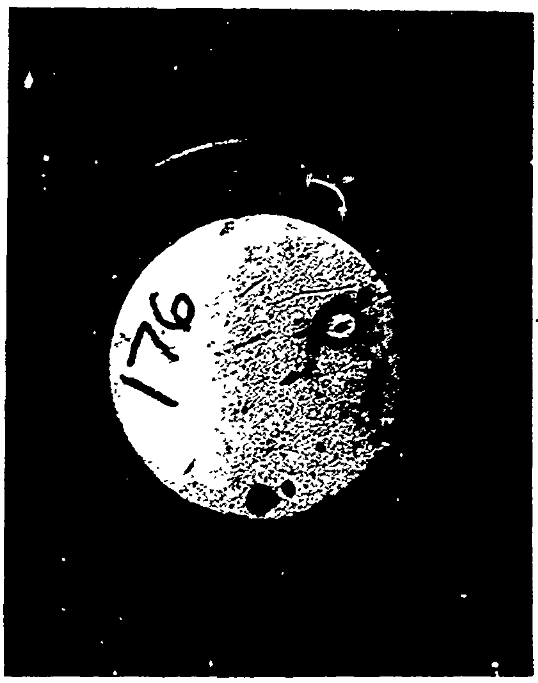
sabot mat'l POLYE

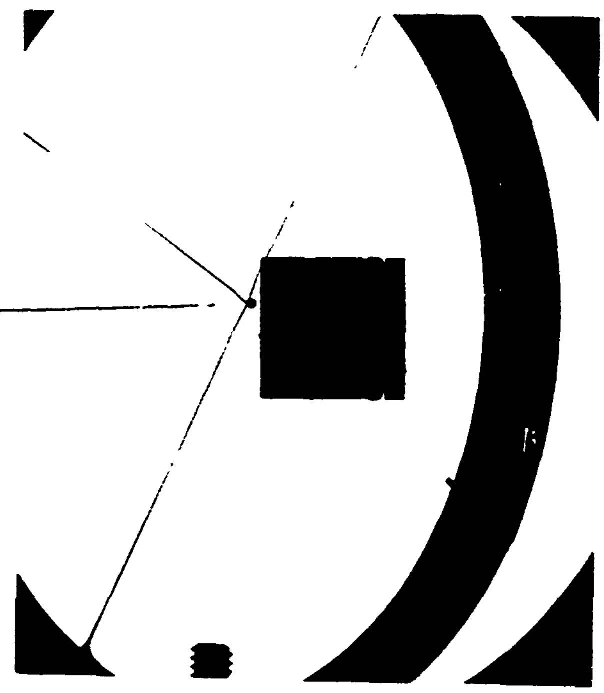
SPECIMEN DATA

material SCFS

group VI

size 1/2"





NOT REPRODUCIBLE

PARTICLE DATA

diameter .052"

composition LEAD

Dv/Do ______

Dh/Do ______

Ms/Mo ______

PRELIMINARY IMPACT DAMAGE

Evaluation: ______

IRREGULAR CRATERS AND IMBEDDED DEPOSITS OF LEAD

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 177

velocity 1060 F/S

pressure 1 ATM

yaw angle 0.5°

sabot dia. .801"

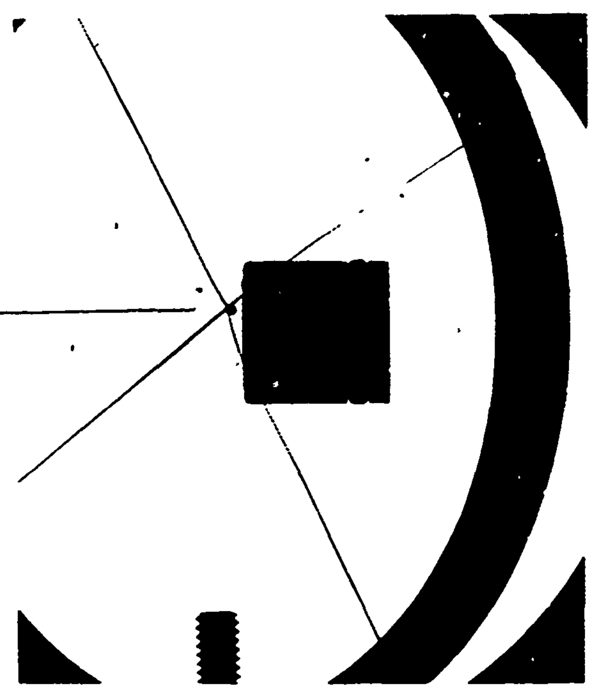
sabot mat'l POLYE

SPECIMEN DATA

material SCFS

group VI

size ½"



NOT REPRODUCIBLE

PARTICLE DATA

diameter .052"

composition LEAD

Dv/Do

Dh/Do

Ms/Mo

PRELIMINARY IMPACT DAMAGE

Evaluation:

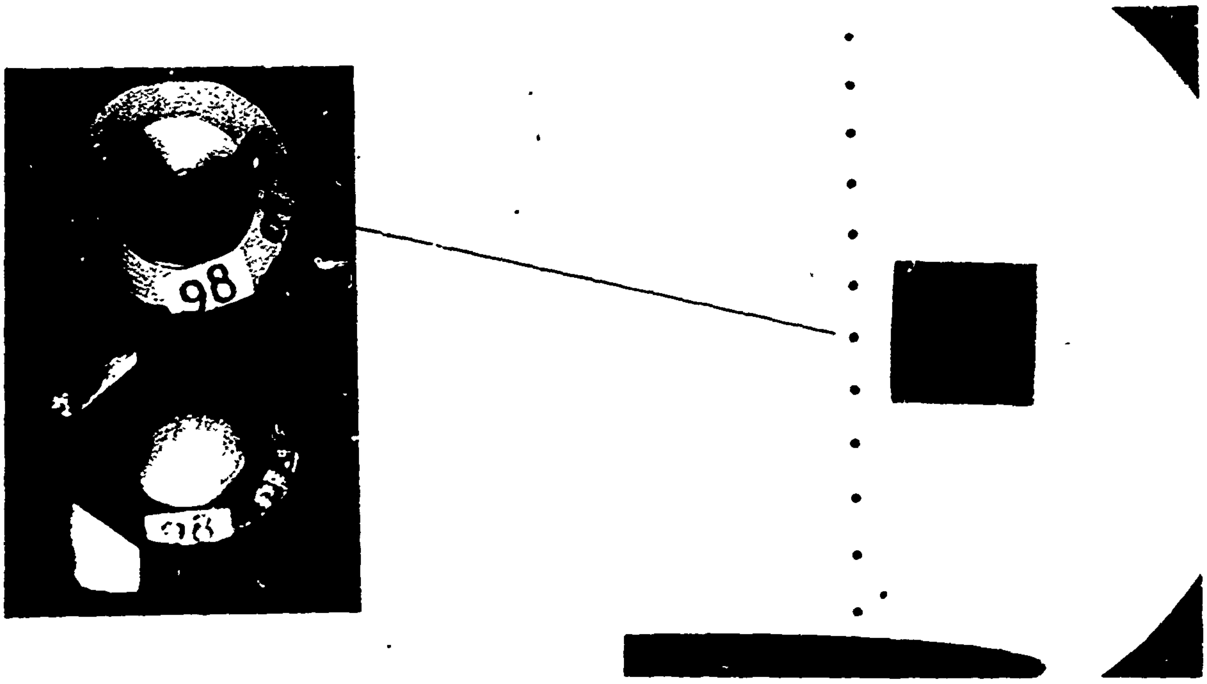
LARGER CRATERS

OF 2 TO 3 mm DIA.

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	98	SPECIMEN DATA	
velocity	842 F/S	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	1°	size	1/2"
sabot dia.	0.8"		
sabot mat'l	POLYE		

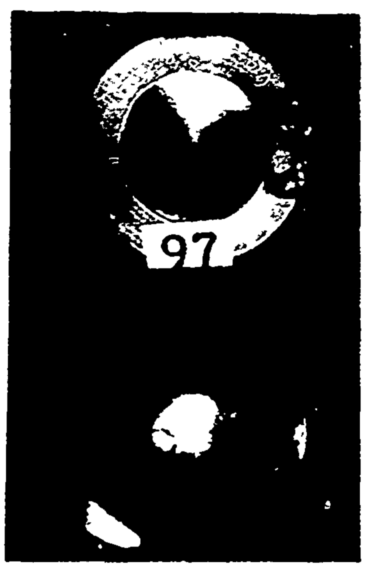


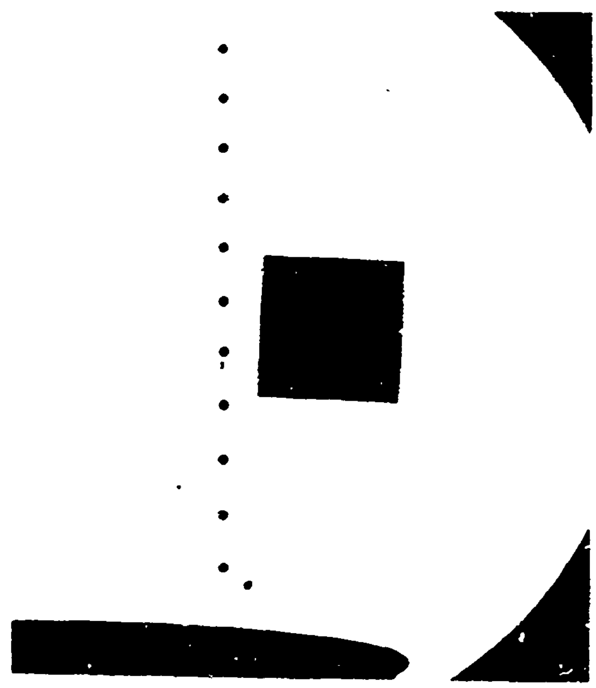
PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.2 mm	Evaluation:
composition	WATER	VERY LIGHT
Dv/Do	1.6 TO 1.9 (EST.)	DEFORMATION
Dh/Do	—	
Ms/Mo	.94 TO .97 (EST.)	

NOLTR 71-113
AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 97
velocity 1076 F/S
pressure 1 ATM
yaw angle 2°
sabot dia. 0.8"
sabot mat'l POLYE.

SPECIMEN DATA
material PLEXIGLAS
group II
size 1/2"





NOT REPRODUCIBLE

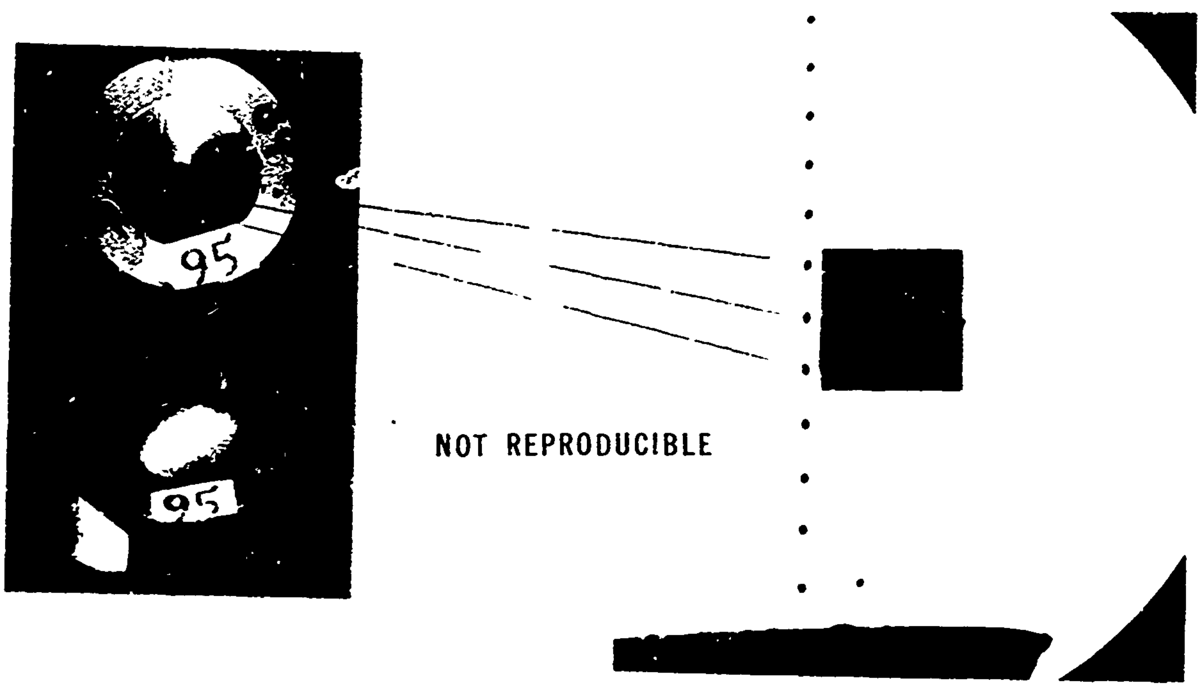
PARTICLE DATA
diameter 1.2 mm
composition WATER
Dv/Do 1.7-1.9
Dh/Do —
Ms/Mo .94-.96

PRELIMINARY IMPACT DAMAGE
Evaluation:
1.2 mm LIGHT
CIRCULAR DAMAGE

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	95	SPECIMEN DATA	
velocity	[illegible]	material	[illegible]
pressure	[illegible]	group	[illegible]
yaw angle	0°	size	[illegible]
sabot dia.	[illegible]		
sabot mat'l	[illegible]		



PARTICLE DATA	
diameter	1.2 mm
composition	WATER
Dv/Do	1.7 - 1.9
Dh/Do	—
Ms/Mo	.94 - .96

PRELIMINARY IMPACT DAMAGE

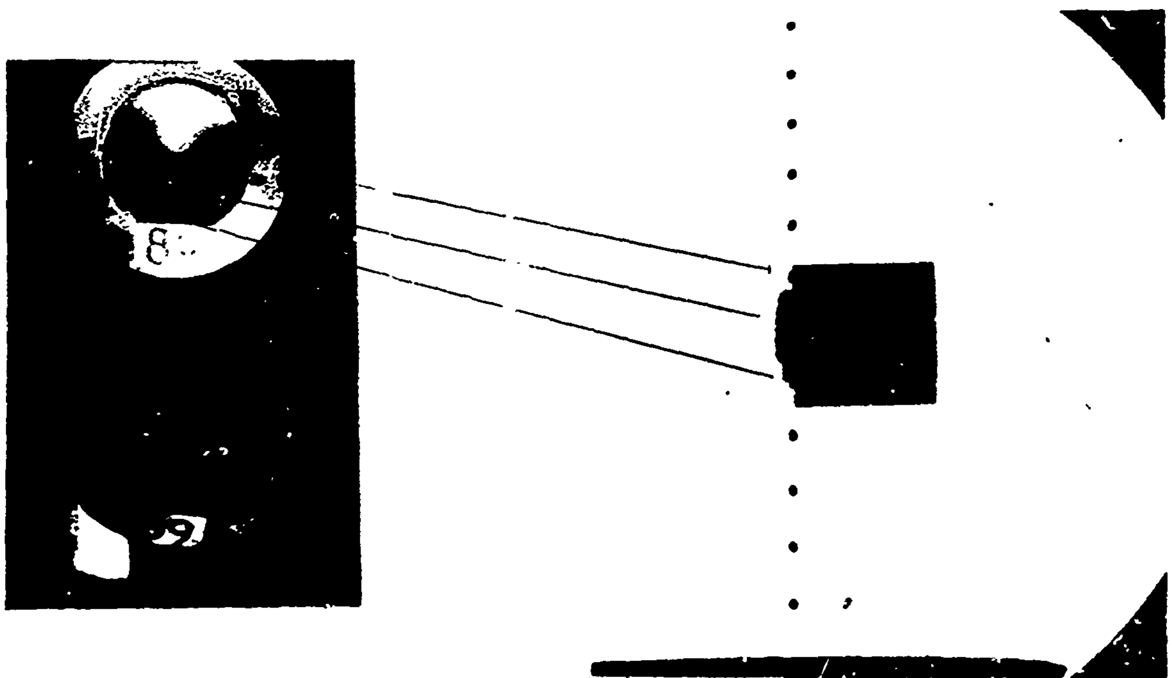
Evaluation:

LIGHT CIRCULAR DAMAGE

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	89	SPECIMEN DATA	
velocity	1260 F/s	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	0°	size	1/2
sabot dia.	0.8"		
sabot mat'l	POLYE.		



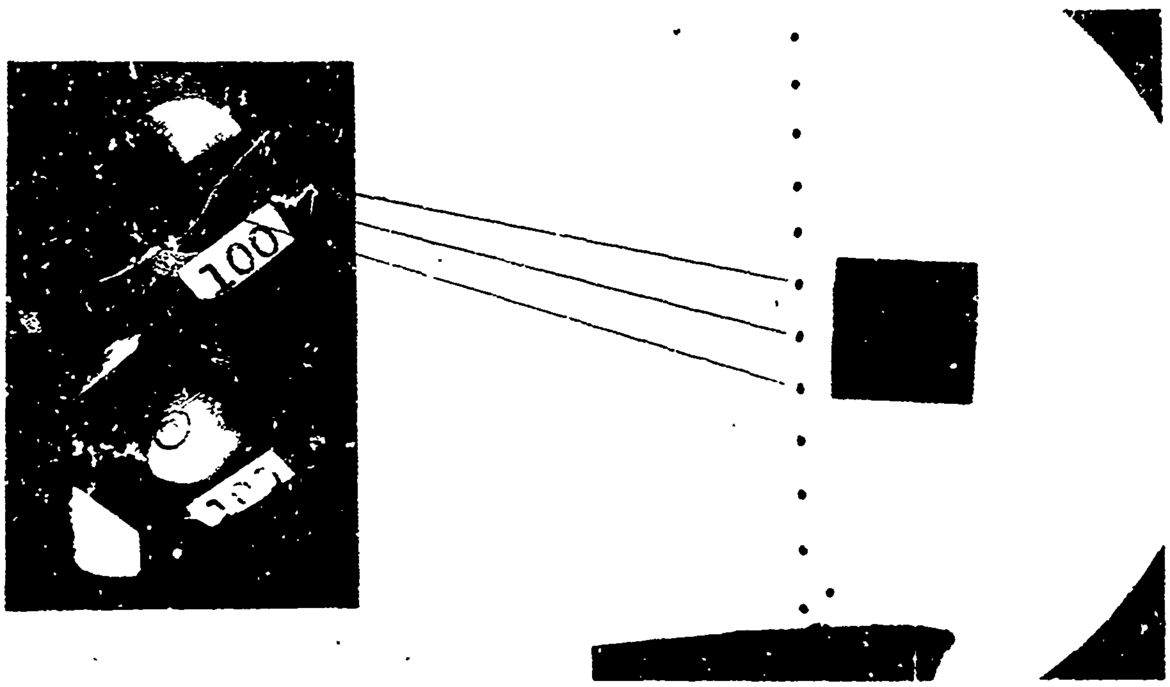
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.15 mm	Evaluation:	
composition	WATER		VERY LIGHT SUB-
Dv/Do	1.7-1.9		SURFACE CRACKS
Dh/Do	—		RINGS ABOUT 1 mm
Ms/Mo	.94-.96		DIA.

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	100	**SPECIMEN DATA**	
velocity	1300 F/S	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	2°	size	1/2"
sabot dia.	0.8"		
sabor mat'l	POLYE.		



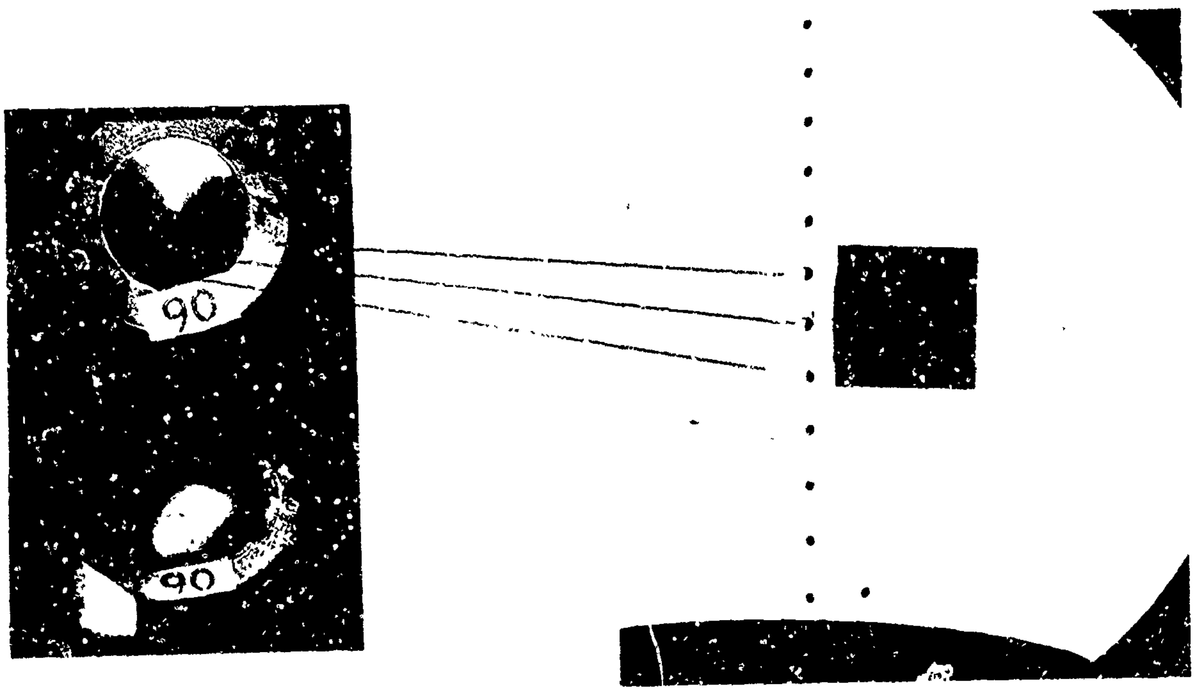
NOT REPRODUCIBLE

PARTICLE DATA		**PRELIMINARY IMPACT DAMAGE**	
diameter	1.2 mm	Evaluation :	
composition	WATER	MODERATE CIRCULAR	
Dv/Do	1.6 - 1.7	CRACKING. RINGS	
Dh/Do	—	INCREASING IN DIA.	
Ms/Mo	.95 - .97		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	90	SPECIMEN DATA	
velocity	1210 F/S	material	PLEXIGLAS
pressure	1 ATM.	group	II
yaw angle	1°	size	1/2"
sabot dia.	.38"		
sabot mat'l	POLYE.		



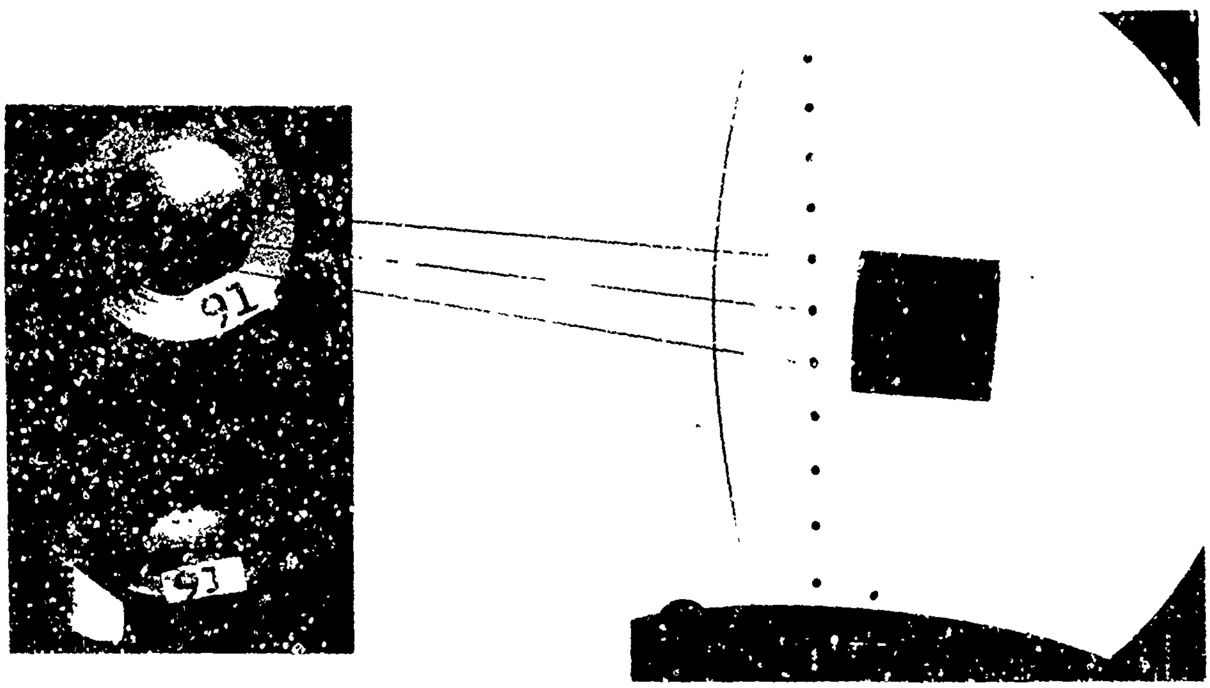
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	1.15 mm	Evaluation:	
composition	WATER	MODERATE CIRCULAR	
Dv/Do	1.6-1.7	CRACKING, ABOUT	
Dh/Do	—	1 mm RINGS	
Ms/Mo	.95-.97		

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	91	SPECIMEN DATA	
velocity	1750 F/S	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	4°	size	1/2"
sabot dia.	0.8"		
sabot mat'l	POLYE.		

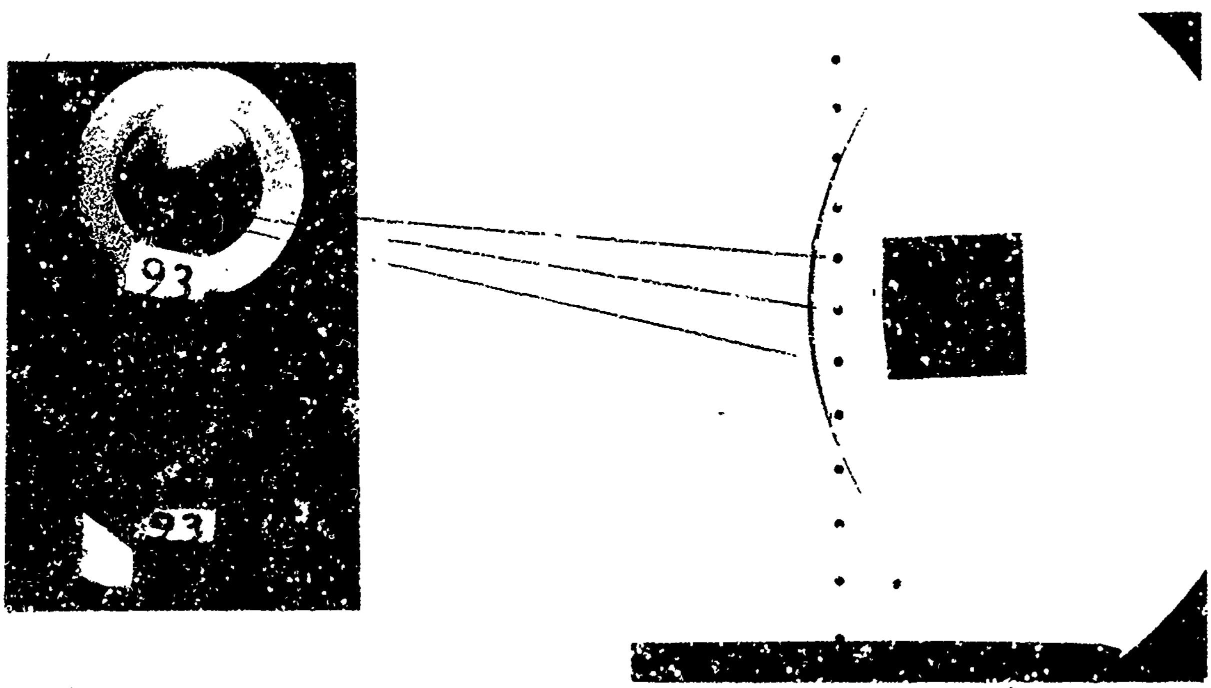


PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.15 mm.	Evaluation :
composition	WATER	CIRCULAR SUB-SURFACE
Dv/ Do	1.65	CRACKING
Dh/ Do	---	
Ms/ Mo	.95-.97	

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	93	SPECIMEN DATA	
velocity	1740 F/S	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	1°	size	½'
sabot dia.	0.8"		
sabot mat'l	POLY C.		

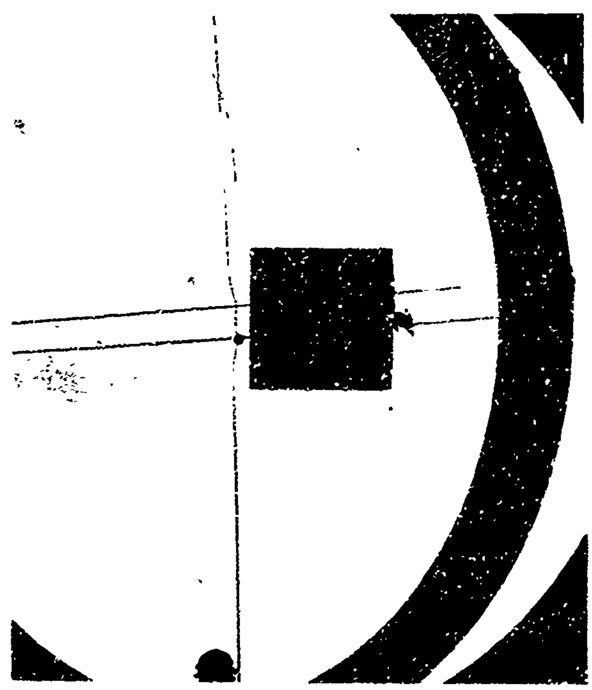


NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	1.2 mm	Evaluation:
composition	WATER	MODERATE CIRCULAR
Dv/Dc	1.5	CRACKING. ABOUT
Dh/Do	—	1 TO 1½ mm DIA.
Ms/Mo	.965	

NOLTR 71-113
AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	191	SPECIMEN DATA	
velocity	623 m/s	material	PLEXIGLAS
pressure	1 ATM	group	II
yaw angle	0°	size	½"
sabot dia.	.801"		
sabot mat'l	POLYE		



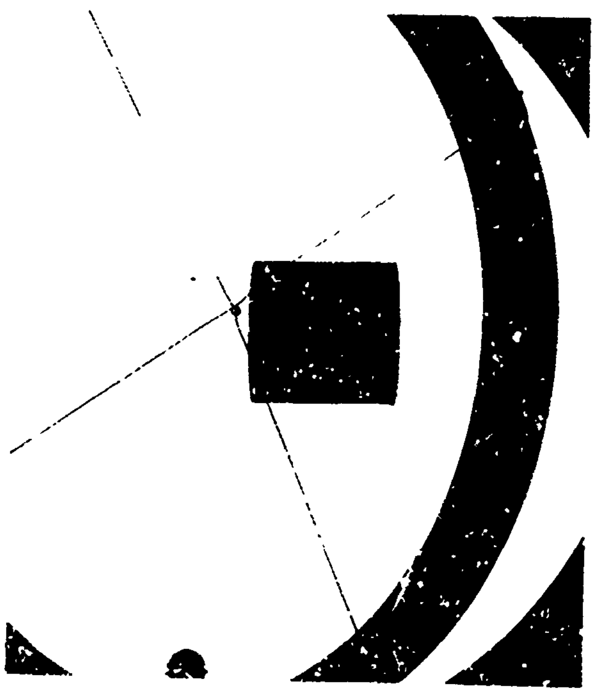
NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE
diameter	.051"	Evaluation:
composition	LEAD	BARELY PERCEPTABLE
Dv/Do		SURFACE DIMPLES
Dh/Do		~ ½ MM DIA.
Ms/Mo		

AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 190
velocity 763 F/S
pressure 1 ATM
yaw angle 3°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material PLEXIGLAS
group II
size 1/2"



NOT REPRODUCIBLE

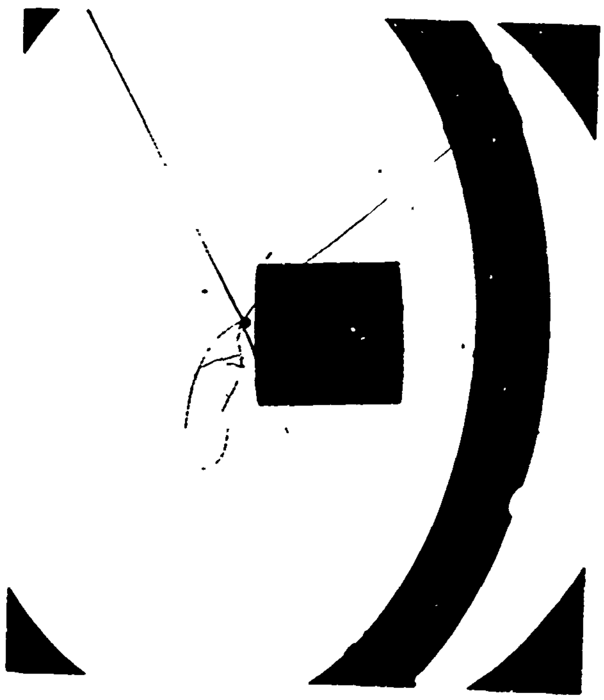
PARTICLE DATA
diameter .051"
composition LEAD
Dv/Do
Dh/Do
Ms/Mc

PRELIMINARY IMPACT DAMAGE
Evaluation :
LIGHT SURFACE
DIMPLES

NOLTR 71-113
AERORHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 187
velocity 871 F/S
pressure 1 ATM
yaw angle 5°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material PLEXIGLAS
group II
size 1/2"



NOT REPRODUCIBLE

PARTICLE DATA
diameter .051"
composition LEAD
Dv/Do
Dh/Do
Ms/Mo

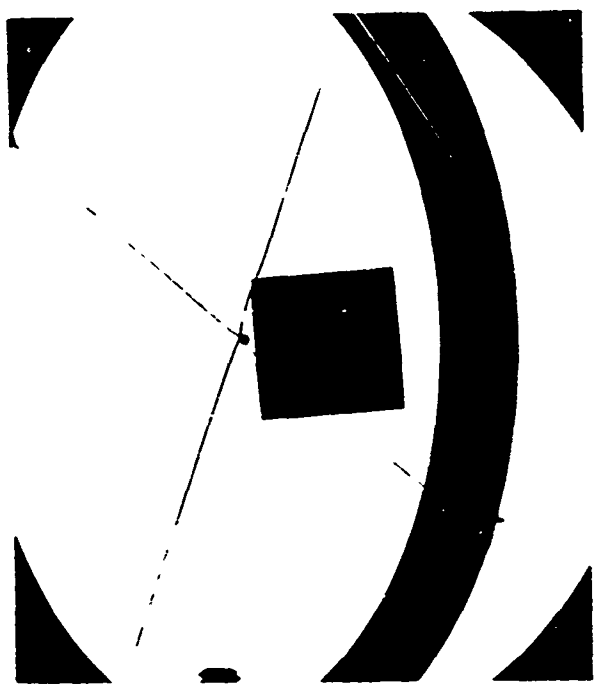
PRELIMINARY IMPACT DAMAGE
Evaluation: RINGS OF CRACKS AND SUB-SURFACE CRACKS. IMBEDDED LEAD DEPOSITS.

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 188
- velocity 1015 F/S
- pressure 1 ATM
- yaw angle 4°
- sabot dia. .801"
- sabot mat'l POLYE

SPECIMEN DATA
- material PLEXIGLAS
- group II
- size 1/2"



NOT REPRODUCIBLE

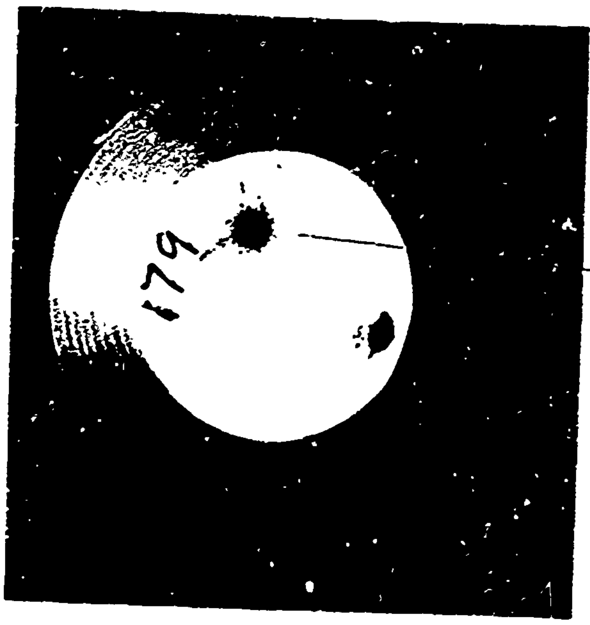
PARTICLE DATA
- diameter .051"
- composition LEAD
- Dv/Do
- Dh/Do
- Ms/Mo

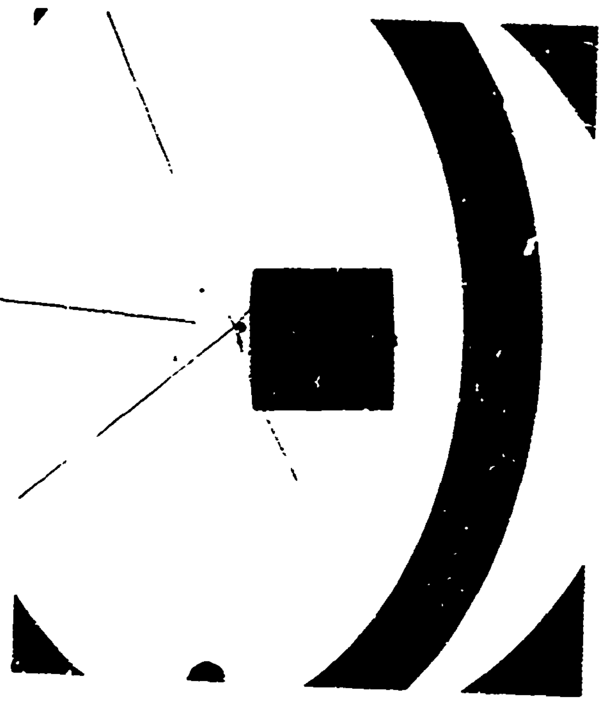
PRELIMINARY IMPACT DAMAGE
- Evaluation:
- HEAVY DAMAGE
- WITH FRACTURING

NOLTR 71-113
AEROPHYSICS RANGE
U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 179
velocity 837 F/s
pressure 1 ATM
yaw angle 1°
sabot dia. .801"
sabot mat'l POLYE

SPECIMEN DATA
material 9606
group III
size ½"





NOT REPRODUCIBLE

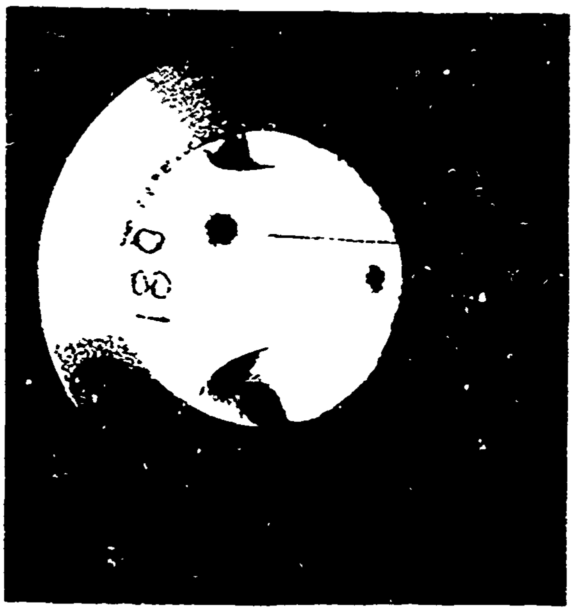
PARTICLE DATA
diameter .052"
composition LEAD
Dv/Do
Dh/Do
Ms/Mo

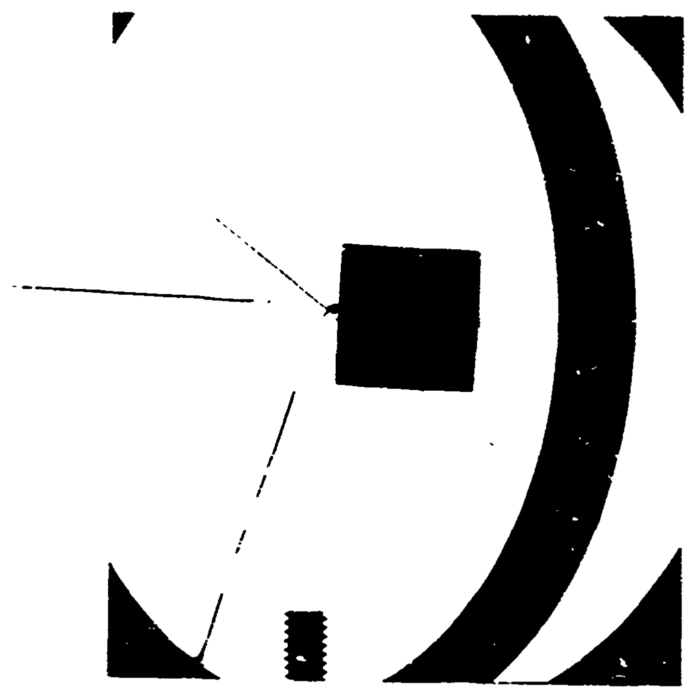
PRELIMINARY IMPACT DAMAGE
Evaluation:
LEAD MARKINGS

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	190	SPECIMEN DATA	
velocity	1190 f/s	material	9606
pressure	1 ATM	group	III
yaw angle	4°	size	½"
sabot dia.	.801		
sabot mat'l	POLYC		





NOT REPRODUCIBLE

PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	.050"	Evaluation:	
composition	LEAD	LEAD DEPOSITS	
Dv/Do			
Dh/Do			
Ms/Mo			

AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER 181

velocity 1425 F/S

pressure 1 ATM

yaw angle 2°

sabot dia. .801"

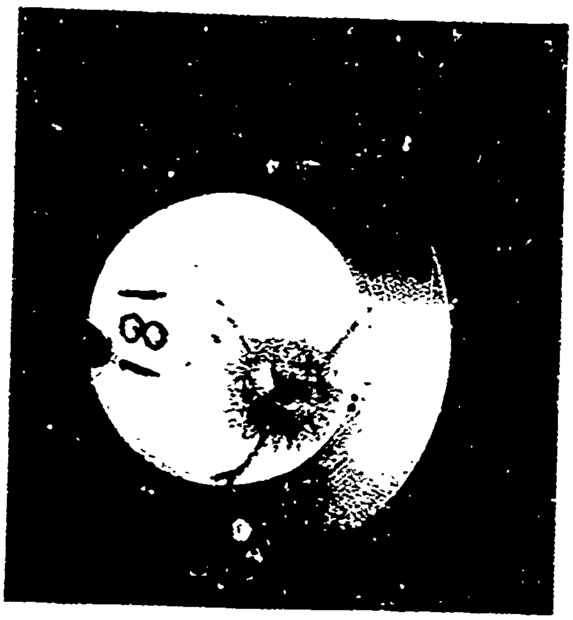
sabot mat'l POLYE

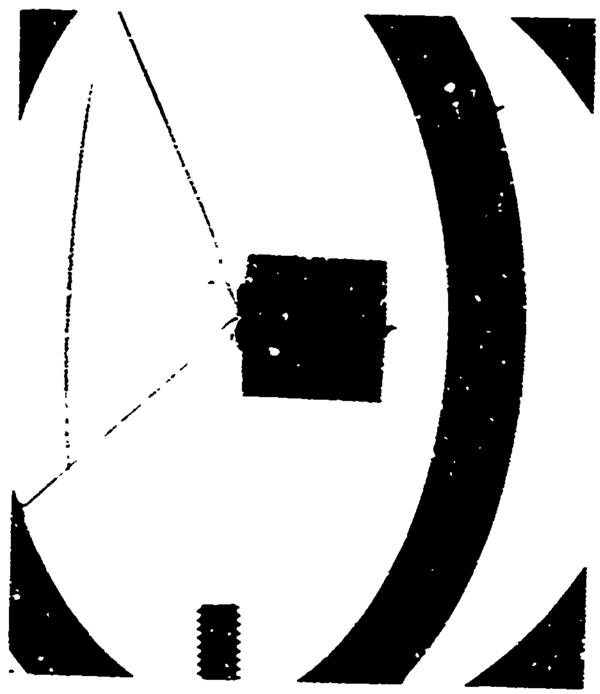
SPECIMEN DATA

material 9606

group III

size 1/2"





NOT REPRODUCIBLE

PARTICLE DATA

diameter .052"

composition LEAD

Dv/Do

Dh/Do

Ms/Mo

PRELIMINARY IMPACT DAMAGE

Evaluation:

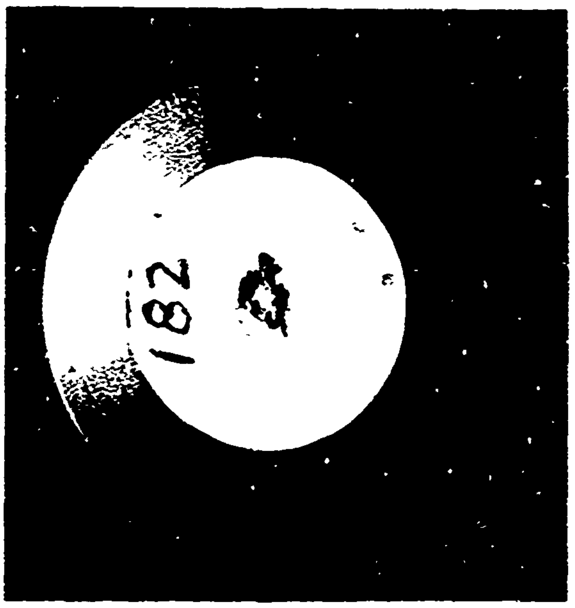
CRACKS OR CHIPS

WITH LEAD DEPOSITS

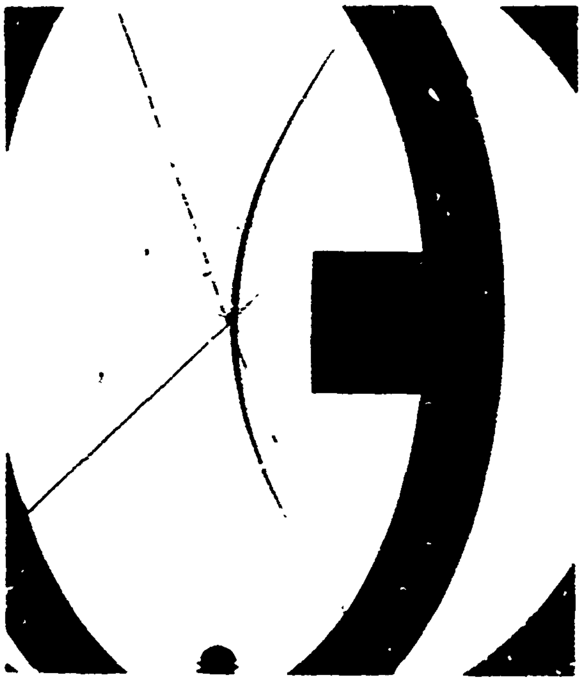
AEROPHYSICS RANGE

U. S. Naval Ordnance Laboratory, White Oak, Maryland

TEST NUMBER	182	SPECIMEN DATA	
velocity	1715 F/S	material	9606
pressure	1 ATM	group	III
yaw angle	0°	size	½"
sabot dia.	.801"		
sabot mat'l	POLYE		



NOT REPRODUCIBLE



PARTICLE DATA		PRELIMINARY IMPACT DAMAGE	
diameter	.052"	Evaluation:	
composition	LEAD	HEAVY DAMAGE	
Dv/Do		3-4 mm CHIPS	
Dh/Do		REMOVED	
Ms/Mo			

APPENDIX C

CHARACTERIZATION OF SLIP CAST FUZED SILICA MATERIALS INVESTIGATED IN PHASE I

This information and the materials used have been supplied by Mr. J. N. Harris of the Georgia Institute of Technology Engineering Experiment Station.

GROUP I

Machined from 3/4-inch diameter slip cast fuzed silica bars.

Impacting surface diamond ground to a smooth finish.

Bars cast from Thermo-Materials Corporation, fuzed silica slip, Lot Number 121570-1. Mean particle size of this slip was 7.2 μm. Fired properties of the 3/4-inch diameter bars from which the 1/2-inch diameter specimens were machined were as follows:

Modulus of rupture = 5050 psi

Elastic modulus = 6.07×10^6 psi

Bulk density = 1.976 GM/CC

GROUP VI

Core drilled from slip cast fuzed silica plates. Surface impacted was "As-cast" surface from plaster mold. Plates were fabricated from Thermo-Materials Corporation, fuzed silica slip, Lot Number 091870. This material has a mean particle size of 9.5 μm. The plates were sintered for six hours at 2200°F. Typical properties for this slip sintered under these conditions are:

Modulus of rupture = 4878 psi
(3/4-inch diameter bars, four-point loading)

Elastic modulus = 5.10×10^6 psi

Bulk density = 1.922 GM/CC

MATERIAL FOR PRELIMINARY EVALUATION WITH SCANNING ELECTRON MICROSCOPE

Cast in open-face plaster mold covered with a glass plate

4 specimens marked "P", impacted surface cast against plaster

4 specimens marked "G", impacted surface cast against glass

Plates for these specimens were core drilled. Plates cast from Thermo-Materials Corporation fuzed silica slip, Lot Number 019870. Firing time was six hours at 2200°F. Mechanical properties should be the same as Group VI.

NOTE: The use of trade names does not constitute Government endorsement or criticism of a material.